SECOND QUARTERLY REPORT

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY

TRANSFORMER DESIGN MANUAL

THIS REPORT COVERS THE PERIOD OCTOBER 1, 1962 TO DECEMBER 31, 1962

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISIONS

CONTRACT NUMBER NOBSR 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ⊛ ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

INTERIM DEVELOPMENT REPORT

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

THIS REPORT COVERS THE PERIOD __10/1/62__ TO __12/31/62__

GENERAL ⬤ ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASSACHUSETTS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NObsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

JANUARY 1, 1963

PURPOSE

The purpose of this project is the investigation, presentation, and verification of data and design methods used to design high power, high voltage, audio frequency transformers. Ratings of these transformers fall within the following characteristics:

(a) Peak power levels from 15 to 350 kilowatts.

(b) Operating frequencies from 20 cps to 20,000 cps.

(c) Peak voltage ratings from 4,000 volts to 28,000 volts

(d) Impedance levels of 300 to 3,000 ohms primary and 10 to 1,200

      ohms secondary.

The scope of this work includes a thorough discussion of the mechanical and packaging aspects of the design, the insulation materials and processing of those materials, and the electrical and magnetic characteristics of audio frequency transformers.

ABSTRACT

During the Second Interim Period, three internal reports were released, and are included in this report.   They are:

    EXHIBIT 1 - The selection of insulation materials to be used
                  for high power audio transformers.

    EXHIBIT 2 - Winding arrangements used in high power audio
                  frequency transformers.

    EXHIBIT 3 - Sample leakage inductance calculation using the
                  method of H. O. Stephens.

Initial work on milestones 4, 6, 9 and 10 is described.   This includes dielectric studies of three fluorogases, absorption tests of inorganic filler materials in silicone oil and many other important aspects pertinent to these four milestones.

IDENTIFICATION OF PERSONNEL

1. Personnel work_ng on this contract during the period covered by this report and the time spent by each are as follows:

John G. Howe Design Engineer Material Components, and Mechanical Design	273 hours
R. D. Smith Design Engineer High Frequency Transformers	126 hours
J. J. Kingsley Specialist	255 hours
R. E. Gearhart Transformer Engineer	161 hours

During the period covered by this report, the following people were contacted:

Mr. Harold Lord   Research Laboratory
                                        General Electric Co.

As stated in the First Quarterly Report, work on this contract has been assigned to two separate teams, one primarily concerned with the electrical design, and the other, the mechanical designs of the transformers within the scopes of this contract.

During the second quarter of this contract, the schedule called for the completion of milestones #2 and #3. Milestone #2, "The Selection of Insulation Materials To Be Used For High Power Audio Transformers", was completed as scheduled and is included as exhibit 1 in this report. Because of a personnel shortage, milestone #3, on "Winding Arrangements Used In High Power Audio Transformers", was not completed until early in the third quarter. However, it was completed in time to be included as exhibit 2 in this report.

Exhibit 1 of the First Quarterly Report included a method of calculating leakage inductance attributed to H. O. Stephens. To clarify this method, a sample calculation is included in this report in exhibit 3.

Some work has been completed on milestones 2, 4, 6, 9 and 10, and is discussed briefly on the following pages.

DISCUSSION - INSULATION AND MECHANICAL WORK DONE DURING THE
SECOND INTERIM PERIOD

First, it should be plainly stated that parts of milestones four and six have been interchanged for better clarity and workforce efficiency. Originally, milestone 4 was to include materials and cooling design for 105 C hot spot transformers and milestone 6 was to be the same thing for 130 C. The revised organization is to include 105 C and 130 C cooling design in milestone #6. This arrangement is much better since now similar things are grouped together.

The following discussion of insulation and mechanical work done in the second interim period includes work done on milestones #2, 4, 6, 9, and 10 which were all worked on during this period. The discussion will follow the organization outlined in the section; "work planned for the second interim period" of the first interim report. It actually amounts to a summary of the work done during the period.

1. Milestone #2 - This milestone on the selection of insulation materials was completed as scheduled and is included as exhibit 1 of this report. Additional references were obtained on this broad subject and the entire reference list is included in the milestone report. An attempt has been made with this milestone to organize the many major insulation materials available with respect to optimum application. This is difficult because each particular transformer requirement is a different combination of many conditions and requirements; some of which are conflicting, such as high power and low weight or nonflammability of the insulation, light weight, and high voltage. The number of actual combinations of conditions is astronomical and with milestone 2, an attempt has made to group some of them and correlate them with proven insulations that are described in published literature.

    The actual selection of the insulation system for the verification units to be made under this contract has been postponed pending the outcome of further tests. It can be stated, however, that the major insulation for the verification units will be either C_2F_6 gas or silicone oil with an inert, displacement material. It appears now that the best compromise would be to make one verification unit with silicone oil and two with C_2F_6 using the oil for the highest voltage and power unit.

2. The dielectric strength of fluorogases - (This work is primarily part of milestone #10 and will be covered in detail with the issuance of that report)

    A gaseous test cell was purchased from the M. J. Seavy Co. of New York City and the dielectric strength of a family of three fluorogases is being determined for various pressures and electrode diameters. The three fluorogases which were selected for evaluation are C_2F_6, C_3F_8, and $C-C_4F_8$.

These three were selected because of their proven thermal stability at temperatures above 200 C. A complete description of each is included in exhibit 1.

For dielectric testing, a hoop-to-plane electrode configuration was selected since it represented the typical configuration in a coil of an end turn or turns to ground. It also allowed the use of different radius electrodes and the subsequent determination of the critical corona start gradient at the electrode. The electrode configuration is shown in Fig. 1.
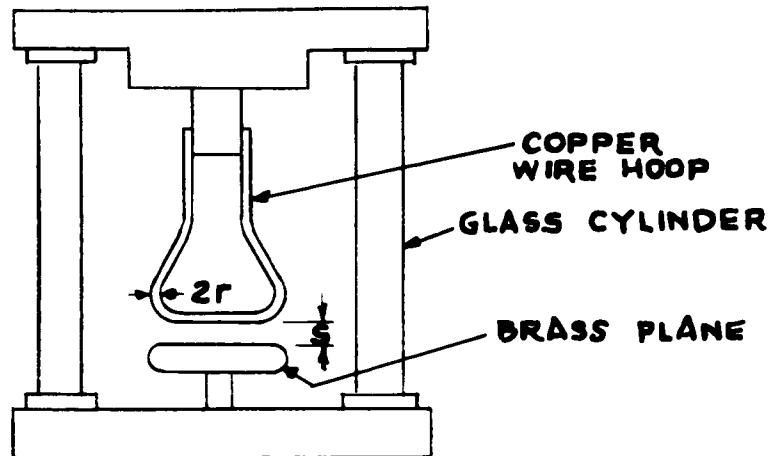

FIG. 1

TEST CELL & ELECTRODE CONFIGURATION

The corona start voltages for various conditions were determined by the cathode ray oscilloscope method described in MIL-T-27A, Fig. 4. The only exception taken was the sensitivity which was set at 1 volt per inch instead of 0.1 volt per inch because the signal voltage reached too high a level with the higher sensitivity.

For each electrode size and gas used, the corona start gradients were determined for spacings ("S" in Fig. 1) from 0.1 to 1 inch. With some of the larger electrode sizes, it was not possible to reach the 1 inch spacing since the voltage required exceeded the 50 KV test berth limit.

$$E = 0.9 \frac{U}{r \ln \frac{s+r}{r}}$$
(1) *

U = indicated corona start RMS voltage

*From "the maximum electrode field strength for several simple electrode configurations" Philips Technical Review September 1941. Configuration = cylinder parallel to plane plate.

- 6 -

As could be expected from the literature (ref. 99, p. 55, 56 in exhibit 1 reference list) the critical corona starting voltage was found to be constant for varying spacing but variable with electrode diameter. A summary of this work done to date is shown in Fig. 2. The slight deviation between the curve for air in Fig. 5 and that shown on page 56 in the cited reference is due to the shielding effect of the hoop and the fact that the test data was for hoop to plane instead of parallel wires.
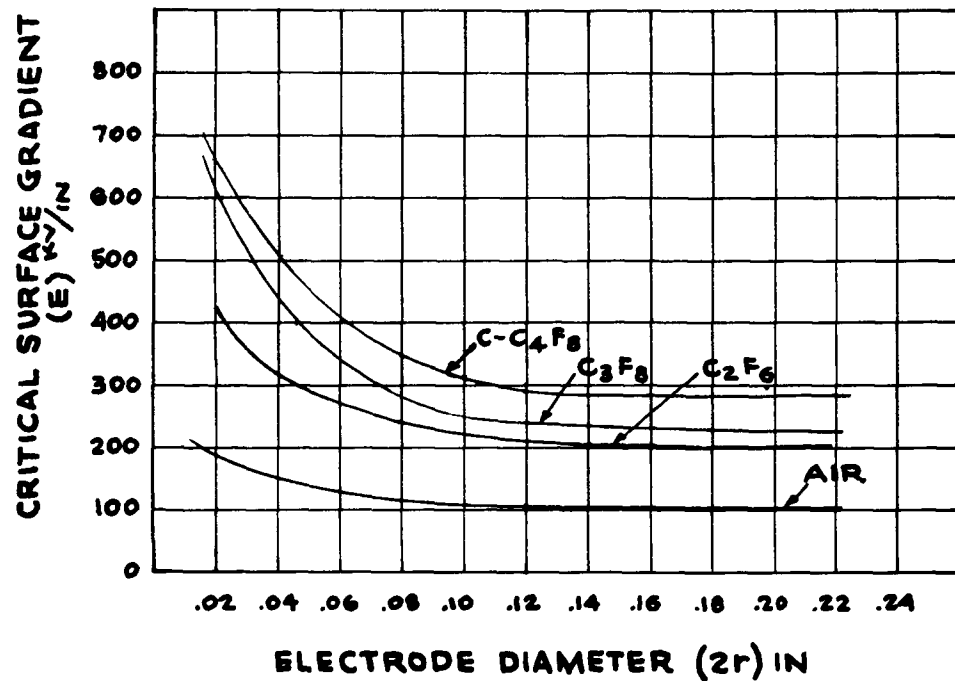

FIG. 2

Critical corona start voltages for various gases vs. electrode diameter

    pressure of gases = 5PSIG

    pressure of air = 0PSIG

The pressure of the gases during this first series of tests was maintained at 5PSIG which is a typical filling pressure for gas filled transformers which are to stay below the 15PSIG minimum for ASTM pressure vessel codes.

This work represents the beginning of work covered by milestone #10 which will end in complete design data for transformers using these materials. In addition to the work described here, data is being accumulated which shows the effect of varying pressure on the corona start and breakdown voltages of the different gases.

3. SF_6 gas - During the early stages of the contract, it was hoped that a study could have been made to determine if SF_6 would be compatible with the usual transformer materials for 10,000 hours at 200 C. Since then, the realization has been reached that this will not be advisable for the following reasons:

    A. Published literature indicates that SF_6 has questionable compatibility with transformer materials at higher temperatures (above 150 C). General Electric's power transformer designs used forced convection of SF_6 to limit temperatures to class A levels. (reference 98 and others in exhibit #1).

    B. The General Chemical Division of the Allied Chemical Corporation issued a report on 3/1/57 which showed that SF_6 was 8-10% decomposed after 270 days exposure to silicon steel at 223 C and 2-4% decomposed after the same exposure to mild steel. (Reference 18 in exhibit #1).

    C. Due to the lack of time available, the availability of other fluorogases with better compatibility, and the fact that such a detailed project as determining the compatibility of SF_6 at 200 C hot spot with metals was not planned in the original contract requisition, it is felt that the time would be better spent on other phases of the contract. It has been shown by other investigations, however, that SF_6 would be a very acceptable gas up to 150 C for indefinite lifes and if limited to this temperature by forced convection or vapor cooling would be the best selection for certain transformer applications. For this reason, it is mentioned in milestone #2 as a possible major insulation for certain combinations of design conditions.

4. Silicone Fluids - Silicone fluids are the only liquid alternatives to gas for the major insulation in a 200 C hot spot transformer. The available proven fluoroliquid with the highest boiling point is FC-43 which boils at 170 C and, therefore, would not satisfy the requirements of the contract. Besides, it is much more expensive than silicone fluid and the high weight and thermal coefficient of expansion make it very undesirable for use except for very unusual circumstances. The silicones on the other hand, are very similar to transformer oil in every respect and could be handled almost interchangeably by an electrical engineer familiar with ordinary transil oil. Since it is a likely candidate for use in this contract, a program was started to evaluate

various inorganic filler materials as displacement media of much lower cost but of dependable, consistent electrical properties. There is some mention of this technique on page 55 of reference #1 (see exhibit 1 reference list), but the intent in that work was to increase heat transfer with the viscous 100 centistoke silicone oil used. The presently available 20 centistoke oil will have a substantially better natural convection rate of heat transfer with or without a filler material than the 100 centistoke fluid used in the referenced work.

Three inorganic materials were obtained and are being evaluated as possible filler materials for silicone oil filled units. Samples of each material were dried, weighed, and vacuum impregnated with 20 centistoke SF(97) silicone oil. At random intervals over a two month period the samples have been weighed to the nearest milligram to determine the amount of oil absorbtion. The results of this test and a brief description of the materials is shown in Fig. 3. As can be seen, each material leveled off almost immediately, but at widely varying percentages by weight of oil absorption. Materials A & C were formulated specifically for this application by an interested vendor and are characterized by lower than usual specific gravity and dielectric constant.
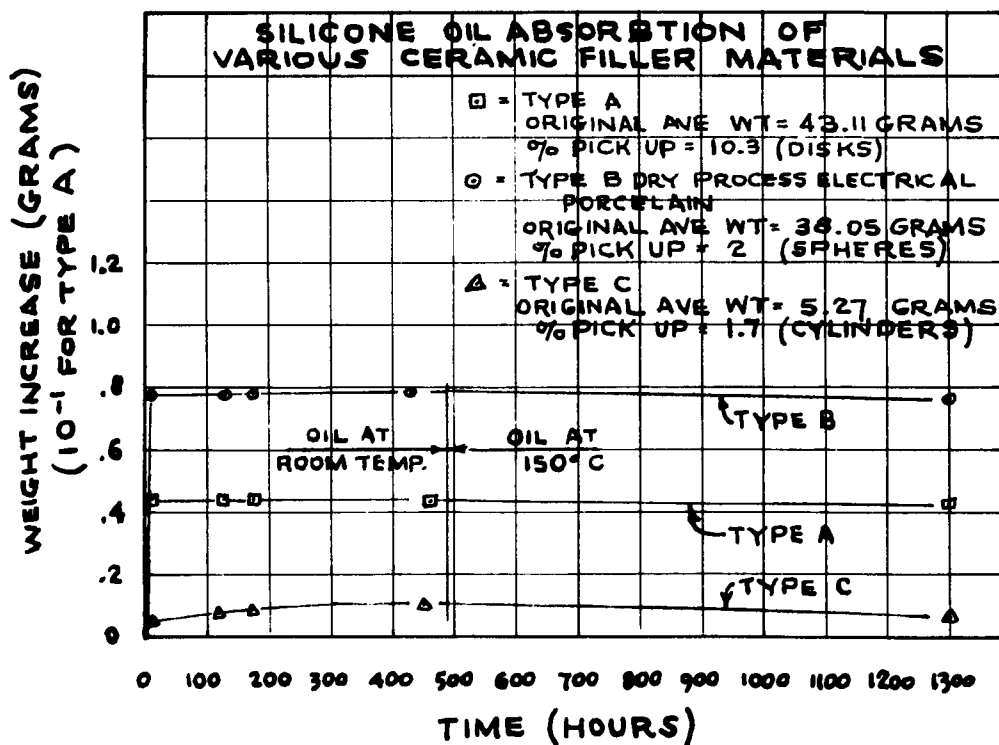

FIG. 3

This work and complete data on the filler materials and their effect on the silicone fluid will be included in milestone #10. As can be seen, however, it is entirely possible to displace up to 50% of the expensive fluid with inorganic solids that cost practically nothing. This will help a great deal in making silicone fluids feasible for large transformers that are covered by this contract.

5. Model Transformers - Six 0.1 KVA transformers have been completed. These units have a 1:1 ratio and the secondary is isolated for 25 KV. Only two tanks were made to save cost as the transformers are interchangeable in the tanks. Two each were made with three different layer insulations:

   1. Fabritherm #76535 .005 thick, a G.E. polyester class H material.

   2. Quinterra - Type 3 - 2 ply, .006 thick - a silicone-asbestos class H material from Johns-Manville.

   3. Kodar - .003 thick - a new terephthalate polyester film from Eastman Kodak of unproven but suspected suitability for use at class H temperatures.

The barrier and form insulation used is NEMA G-7 glass silicone laminate in all cases. The turn insulation is ML enamel.

One of each of the three pairs of transformers has thermocouples in the primary and secondary for determination of thermal rises under a variety of conditions such as different loadings, different major insulations, etc. The other of each of the pairs does not have thermocouples so it can be used for high voltage dielectric studies between the isolated secondary and ground. It is expected that a great deal of design data will be obtained from these simple units. They will also be used to substantiate theoretical calculations of both thermal and dielectric properties for the materials used.

6. Solid Insulations - Many vendors were contacted and literature obtained. Four solid insulations were purchased for the model transformers as described in section 5 above. Dielectric strength data for these materials in their basic form has been obtained in various atmospheres but has not yet been evaluated. The Kodar shows exceptional measured dielectric strength of three to four KV per mil in a three mil film. Due to its good dielectric properties, it will be evaluated carefully for thermal and life performance at class H temperatures. Negotiations have been started with a supplier (The Arvey Corporation of Jersey City, New Jersey) for the production of laminated Kodar and Quinterra which would conceivably combine the electrical properties of the Kodar with the thermal and cut through resistance of the asbestos. Samples have been received and will be evaluated soon.

Work will continue in this area as a very important part-of both milestones four and ten.

7. Cooling and Mechanical Considerations - Work has started on milestone six which is the cooling and thermal design for 105 and 130 C and the part of milestone ten concerning 200 C hot spot cooling. The moduli of natural convection have been calculated for ? vide range of temperatures at constant densities for eight materials; air, C_2F_6, C_3F_8, $C-C_4F_8$, oil, askarel, silicone, and FC-43. It will now be possible to calculate the natural convection coefficients for these materials for any temperature range.

Form letters have been sent to all potential vendors outlining our requirements for internal blowers and feed-through bushings. The blowers would be used for forced circulation of the gas and would naturally require a larger motor for fluorogas than for air.

There are very few bushings available for air to gas use which are corona free at the higher voltages. The problem has been outlined to interested vendors and their response indicates substantial interest and eventual availability of suitable bushings.

8. Artificial Circulation vs. Evaporative Cooling - For this contract, evaporative cooling with a fluoroliquid is out of the question since the hot spot temperature with this method is limited to 170 C because of the boiling temperature of FC-43. Although there may be other materials available, they are not covered in the published literature for this type of use and their evaluation would be beyond the scope of the contract.

Evaporative cooling has been used in three basic ways.

A. With the heat producing units submerged in the liquid.

B. With the liquid being naturally drawn into the hot areas by wicking or some form of capillary action.

C. With the liquid being circulated and sprayed onto the hot areas by a mechanical pumping source.

With each method, heat transfer rates far in excess of those obtained with natural convection of a liquid are obtained. However, as with any system, there are disadvantages that must be weighed carefully before a selection is made. Basically, they are as follows:

Method A requires large quantities of extremely expensive liquid which is also very heavy. The pressure rise due to the excessive coefficient of thermal expansion plus the rejection of absorbed gas (required for

bellows action over the liquid) results in excessive pressure rises which exceed the lower limit of the ASTM pressure vessel code. This makes the construction and maintenance of a suitable tank complicated for units of any substantial size.

Method B is a better compromise since it is conceivable that pressure rises and the cost and weight of the required fluoroliquid can be kept within reason. To the writer's knov.ledge, however, the dependable wicking of coolant to hot spot areas has not been demonstrated in larger transformers. The proper maintenance of a reservoir of coolant for wicking requires operation of the unit in a consistent position.

Method C is described in Westinghouse patent #2,561,738 and is more applicable to large stationary power transformers. Since a pump and fluid piping are required to circulate the cooling liquid, it may be best to eliminate the fluid and its associated problems entirely and just force the convection of the dielectric gas. This leads to the second part of this discussion, the forced convection of the gas.

It has been demonstrated commercially that natural convection alone of the insulating gas is enough cooling for properly designed power trans- formers (See reference #87 in exhibit 1). In fact, far more commercial transformers of this type have been sold than both forced convection gas and liquid evaporative cooled types together. The advantages of the natural convection-gas type are obvious. They are lightest in weight and do not require additional power, fans, pumps, ducts, or piping. When the losses are too great for natural convection, however, all of the above schemes should be considered and in some cases will amount to a standoff in complex- ity and problems. But, since the contract this work is done for stipulates a 200 C hot spot, and since evaporative cooling of transformers is already well described in published literature, the forced convection approach will be used if necessary for the verification units of this contract. In any case, design techniques for this method of cooling will be described in milestone #10 under the cooling of 200 C hot spot units.

9. Milestone #4 - As was stated at the beginning of this discussion, parts of milestone 4 and 6 have been interchanged for the sake of better organization of material, clarity, and manpower utilization. Milestone 4 now includes all design data and related information concerning insulation materials and usage for 105 C and 130 C hot spot but not the cooling calculations for these temperature ranges. Due to the fact that the use of solid major insulations such as epoxies and silicones is beyond the scope of this contract and die- lectric gases are more commonly used at higher hot spot temperatures, milestone 4 will be restricted to liquid major insulations and compatible solid materials which will mainly be cellulosic in nature. This milestone was 50% completed during the second interim period. As was planned in the original contract proposition, a comprehensive discussion of the appli- cation of thermally upgraded papers and pressboards will be included. This section is important because it is with these less glamorous class A and B materials that most transformers will actually be made.

GENERAL ELECTRIC COMPANY

PROJECT PERFORMANCE AND SCHEDULE

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

CONTRACT No. NOBSR-87721

DATE: DECEMBER 31, 1962

PERIOD COVERED: 10/1/62 TO 12/31/62

	1962						1963												
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

MILESTONE 1

PROCEDURE COVERING DESIGN PRACTICE FOR CALCULATING:
(A) DISTRIBUTED CAPACITANCE
(B) LEAKAGE INDUCTANCE
(C) OPEN CIRCUIT INDUCTANCE

MILESTONE 2

PROCEDURE STATING CHOICE OF MATERIALS FOR INSULATION SYSTEMS FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGNS AFTER HAVING COMPLETED LITERATURE SURVEY AND STATE OF ART REVIEW.

MILESTONE 3

PROCEDURE COVERING WINDING ARRANGEMENTS AND DESIGN FORMULAE FOR CALCULATION OF DISTRIBUTED CAPACITANCE AND LEAKAGE INDUCTANCE FOR THESE WINDING ARRANGEMENTS.

MILESTONE 4

PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.

MILESTONE 5

PROCEDURE COVERING CALCULATION METHODS FOR FREQUENCY RESPONSE OF VARIOUS EQUIVALENT CIRCUITS.

MILESTONE 6

PROCEDURE COVERING DESIGN PARAMETERS FOR COOLING FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.

MILESTONE 7

PROCEDURE COVERING PROCEDURE FOR CALCULATING CORE AND COPPER LOSSES.

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	1962						1963												
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

MILESTONE 8

COMPLETE DESIGN (ENGINEERING AND DRAFTING) AND RELEASE TO MANUFACTURING SECTION OF HOLYOKE G.E. FOR MANUFACTURE OF THREE VERIFICATION UNITS.

MILESTONE 9

PROCEDURE COVERING MECHANICAL DESIGN PARAMETERS AND COMPONENT SELECTION FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGN.

MILESTONE 10

PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION AND COOLING FOR 200 C AND CALCULATION FORMULAE FOR WINDING RISE.

MILESTONE 11

BUILD VERIFICATION UNITS AND START TO TEST AREA FOR TEST.

MILESTONE 12

ISSUE TEST REPORT ON VERIFICATION UNITS.

MILESTONE 13

COMPLETE PROJECT - MANUAL TO PRINTER.

GENERAL ELECTRIC CO.

PROJECT PERFORMANCE AND SCHEDULE

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

Contract No. NObsr-87721   Date: December 31, 1962

                                            Period Covered: 10/1/62 to 12/31/62

Legend   ███████ - Work performed

                  ▣   - Schedule of Projected Operation

Estimated completion in percent of total effort expected to be expended
(not chronological)

	% As Of Oct. 1	% As Of Dec. 31
1. Inductance and capacitance calc.	100	100
2. Selection of insulation system	70	100
3. Winding arrangements	0	75
4. 105 C cooling and insulation	10	50
5. Core and copper losses	0	0
6. 130 C cooling and insulation	5	25
7. Frequency response	0	0
8. Complete sample designs	0	0
9. Mechanical design	0	10
10. 200 C cooling and insulation	10	30
11. Build sample units	0	0
12. Test sample units	0	0
13. Final report	0	0

WORK PLANNED FOR THE THIRD INTERIM PERIOD

Insulation and Mechanical

1. Milestone #4 will be completed.

2. Milestone #6 will be brought nearly to completion.

3. Milestone #9 and 10 will be brought to a stage where sufficient design information will be available to begin milestone #8, the design of the verification units.

4. Basic dielectric studies will continue on the gases and solid insulations for 200 C hot spot service.

5. The model transformers will be tested for thermal and dielectric performance with a wide variety of conditions and major insulations. The data obtained will be compared against the theoretical calculations.

6. Life studies for verification of compatibility will be started for the 200 C hot spot material. These studies will be at various higher temperatures so Arrhenius reaction rate curves can be extrapolated to the normal temperatures.

7. The effect of frequencies up to 20 KC on the insulations used will be determined either from published literature or empirically.

Electrical

A milestone report is scheduled during the third interim period covering procedures for calculating core and copper losses at high frequencies. Because a high power audio frequency generator required for this work is not yet available, a schedule change is required. The generator has been ordered by General Electric Co. and is scheduled for delivery February 8, 1963. Because of the delivery schedule of this equipment, the work originally scheduled to be completed under milestones number 5 and 7 has been interchanged.

During the third interim period, the following is planned.

8. Complete milestone #3. Because we did not obtain the additional personnel required for this project as originally planned, milestone #3 was not completed on schedule. It was completed early in the third interim period, but in time to be included in this quarterly report.

9. Complete milestone #5 (formerly milestone #7). Various equivalent circuits will be shown, and equations for frequency response, characteristic impedance, and phase shift will be derived. Model transformers will be built and their actual frequency response compared with the calculated response.

10. Start milestone #7 (formerly milestone #5). Model core and coils will be built and tests started to determine the core and copper losses.

EXHIBIT I

MILESTONE REPORT #2

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

THE SELECTION OF INSULATION MATERIALS TO BE USED FOR HIGH POWER AUDIO

TRANSFORMERS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NOBsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9,99

GENERAL ⬤ ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

THE SELECTION OF INSULATION MATERIALS TO BE USED FOR HIGH

POWER AUDIO TRANSFORMERS

SCOPE

As indicated in the requisition, the scope of contract NObsr-87721 includes audio transformers in the following ranges:

Power: 15 to 350 KW
Frequency: 20 to 20,000 cycles
Peak Voltage: 4 to 28 KV (operating)
Hot spot temp: 105, 130, and 200 C

In addition, the following classes of MIL-E-16400 electronic equipment have to be considered:

Class	Ambient Range (Operating)	
1	-54	+65 C
2	-28	+65 C
3	-40	+50
4	0	+50

Finally, the factors of flammability, weight, size and cost have to be taken into account.

The point in stressing the extreme scope of the contract is that nearly every insulation system known would be needed to best satisfy each of the combinations of the above considerations.

TYPES OF INSULATION

Before going further, the phrase "insulation system" needs clarification. This is an all inclusive phrase that is often used loosely. For this discussion, the "insulation system" will include the following six parts:

1. Major Insulation - This is the filling insulation that takes up all spaces not occupied by the other insulations referred to below. It can be either a gas, liquid, or a solid. Its main purpose is to provide resistance to electrical breakdown between the high potential areas and the case and mechanical parts of the transformer. It usually impregnates all voids between other insulation components. The major insulation also serves the second purpose of removing most of the heat generated in the transformer.

- 1 -

2. Layer Insulation - This is a solid insulation in thin sheet form used as a barrier to breakdown between adjacent winding layers.

3. Barrier Insulation - This is a solid insulation usually thicker than a thin sheet (more than .030 thick) and used to prevent breakdown between parts of different potential other than between layers.

4 Turn Insulation - This is the thin solid insulation applied to the conductor itself to prevent turn to turn breakdown between adjacent and nearby turns

5 Form Insulation - This is heavier insulation which serves a primary mechanical function such as a winding cylinder or a coil support.

6. Varnish Insulation - Varnish may or may not be used in a transformer to provide mechanical support or resistance to moisture and other contamination. Its use depends on the mechanical, environmental and electrical duty expected for the unit. The varnish may be vacuum impregnated or it may be just a dip resulting in a surface coating.

Naturally, all six parts of the insulation system have to have proven compatibility with each other over the life and temperatures expected for the transformer. The problems involved in selecting a complete, compatible insulation system for each of the combinations of conditions to be covered by this contract are many and complex. It will be the intent of this discussion to show when each of the many insulation systems should be used.

The most important component in the insulation system is the major insulation and it is on this part that most attention will be focused. Tables I & II show when each of thirteen major insulations discussed in this paper should be used for 72 different combinations of operating conditions. In about half of the 72 combinations, only one insulation system is mentioned. In this case, there is practically no question as to which system should be used. In the other half of the combinations where up to five systems are mentioned, there is some question as to which system will best satisfy the condition combination. The exact selection in this case would depend upon the exact rating of the unit and the relative importance of cost, weight, size, quantity etc Wherever more than one system is mentioned, an attempt has been made to list them in order of decreasing preference. In all cases, cost has been kept foremost in importance.

It was originally hoped that one system for each of the three hot spot temperatures would suffice but as can be seen, this is not possible if the work is to be complete. In actuality, the use of thirteen major insulation systems should not be any more complex than two or three since for electrical design purposes, they can all be treated similarly. The various property values need only to be used in the proper electrical equations. The same is true for

heat calculations although there may be need for additional means of heat transfer to the usual three of convection, conduction, and radiation. For units of high power or narrow frequency range, the addition of vapor cooling or forced convection may be required.

It should be noted that most of the thirteen major insulation systems discussed are already in use and have been covered in some detail in various published works. A brief description of each system is given:

MAJOR INSULATIONS

A. Transil Oil: The most common dielectric major insulation. Excellent for use up to 130 C hot spot (in the coil) whenever flammability of the major insulation is acceptable. References - 35, 38, 70, 71, 92, 93.

B. Askarel Oil: Developed in the 1930's by GE for use where non-flammability of the major insulation is required. Contamination is important since it effects dissipation factor drastically. Temperature also affects dissipation factor and this limits the use of askarel to 130 C hot spot operation. It should be noted that askarels have a high dielectric constant of 4 to 5. This will severely limit its use in audio or pulse transformers where the capacitive effect of this property is important. References - 60, 62, 70, 71, 94, 95.

C. Air Insulated Dry Type: The most common low voltage major insulation due to least cost. Susceptible to contamination and humidity. References too numerous to mention.

D. Gas, $c-C_4F_8$: This is a higher boiling point gas which is commercially available. Except for its boiling point which is -6 C, it would be one of the most ideal dielectric gases. It should be seriously considered for any MIL-E-16400 class 4 applications due to its inertness and higher dielectric strength than the other gases. References: 62, 76, 83, 86, 102 The use of this gas as a dielectric material is covered by General Electric patent #2,886,625.

E. Gas - C_3F_8: This is a very stable dielectric gas presently in use by the Medium Power Transformer Dept. of the General Electric Co. Its boiling point (-38 C) limits its use to MIL-E-16400 class 2 applications. References - 17, 20, 21, 62, 81, 86, 87.

F. Gas - C_2F_6: This gas is commercially available and has a very low boiling point of -78 C making it acceptable for MIL-E-16400 class 1 & 3 use. Due to its slightly lower dielectric strength than the other gases, it has not been completely evaluated for transformer use. Like the other fluorocarbon gases, it is very inert to chemical degradation at 200 C hot spot temperatures. It could prove to be an ideal gas for wide temperature range military use. References - 19, 86, 96.

G. Gas - SF_6: This is the most common gas for dielectric use. It is presently used for some power transformers, x-ray transformers, and also for recently introduced circuit breakers. It is limited by chemical breakdown to 150 C although there is some question about this limitation for 10,000 hour life military transformers. It is by far the cheapest dielectric gas other than air or nitrogen. References - 14, 20, 21, 25, 29, 58, 62, 86, 88.

H. Gas and Fluoroliquid Cooling: This technique combines the low cost and non-flammability of the gases with the excellent heat transfer properties of a boiling fluorocarbon liquid. Its use has been described in several different variations. Certain applications justify the disadvantages of wider pressure variation, cost, and additional plumbing required. The gas used would be one of those mentioned above, although solubility of the gas in the fluorocarbon liquid is important and will influence selection. References - 1, 11, 13, 31, 73, 84, 85, 91, 103.

I. Fluoroliquid: Two fluoroliquids have been used for transformer major insulation. These are both produced by the Minnesota Mining and Manufacturing Company and are designated FC-75 which is a fluorinated cyclic ether with the formula $C_8F_{16}O$, and Fc-43 which is perfluorobutylamine with the formula $(C_4H_9)_3N$. The Fc-75 has a boiling point of approximately 102 C and is the liquid usually used for evaporative cooling. The Fc-43 boils at 177 C and has been used for complete submersion of a transformer coil and core where evaporative cooling is not used. The proper combination of the two liquids will give evaporative cooling at any desired temperature between their two boiling points.

Both liquids are excellent dielectric major insulants. They both have most of the properties desired in a perfect dielectric liquid. They do, however, have three major disadvantages the combination of which has drastically limited their use in most military electronic equipment. These are:

1. Cost: The FC-75 costs just over $100 per gallon, whereas, FC-43 costs over $300 per gallon. This fact alone would restrict their use in anything but very small quantities such as an evaporative cooling additive in a large transformer such as is within the scope of the contract.

2. Expansion: The thermal coefficient of expansion is about twice that of conventional oils requiring extensive provision for this property when the fluids are used as the major insulation.

3. Weight: These liquids are about twice as heavy as transil or silicone oil, although, they are only slightly heavier than an askarel. This means that the volume advantage of a compact transformer using these liquids is often offset by increased weight over a well designed unit of conventional materials.

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These disadvantages restrict their use to only those applications where their unusual heat transfer properties can be put to use. This situation is not likely to occur in a broad-band audio transformer where the designer would not be "pushing" the copper and core densities because of the electrical infidelity that would occur if he did.

It should be mentioned, however, that these liquids should not be ruled out completely since their excellent dielectric strength, arcover healing qualities, low dielectric constant, inertness, and nonflammability make them justifiable in some applications. References: 1, 7, 11, 13, 45, 62.

J. Silicone Liquids Other Than Sil-Phenylene: The common polydimethyl-siloxane liquids have properties which warrant their use as major insulations in high temperature transformers. They are available in a wide range of viscosities and are chemically and electrically stable over a wide range of frequencies and temperatures. Electrical and mechanical design with these liquids would be much the same as with transil oil since all the important properties are similar with the exception of thermal stability which is much better with the silicones. Their cost is about $20 per gallon which is not quite as prohibitive as that of fluoroliquids, although it certainly requires close consideration.

The two major disadvantages of the polydimethylsiloxane liquids are as follows:

1. Flammability: These liquids cannot be considered non-flammable, since they have a closed cup* flashpoint of about 350 F compared with about 230 F for transformer oil. (This value will be substantially less than the open cup flash point test which is the one commonly referred to).

2. Lack of arc resistance: In the advent of an internal electric arc, there will definitely be severe degradation of these liquids resulting in successively less arcover values. This is a dubious disadvantage since a properly designed transformer should never be close to an arcover condition. If a conventional transformer arcs over inside, it is usually ruined so that normal, good design takes this into consideration. Even with liquids that are resistant to arcover contamination, there is good possibility that solid insulation in proximity to the breakdown will be damaged enough to fail the unit. References - 2, 3, 7, 12, 15, 16.

K. Sil-phenylene Liquids: These are recently announced silicone fluids which were specifically designed to decrease the two disadvantages mentioned for the polydimethylsiloxane fluids. They are available as the General Electric Silicone Products Department XF1000, 1050, 1051,

*ASTM Method D93-58T

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and 1053. They are standard methylpolysiloxane fluids with all the traces of low volatile fragments removed. The different grades have varying degrees of non-flammability and arc resistance. The XF1053 has a closed cup flashpoint of 425 F. This is above the Air Force require-ments for extreme temperature dielectric coolants for use in advanced missiles and space crafts. Unfortunately, these are developmental materials with prices in the $100 per gallon range, but they certainly should be considered in lieu of fluoroliquids. References-15, 49.

L. Epoxy Potted: Hundreds of thousands of small low voltage transformers have been impregnated and potted with epoxy resins. This technique is applicable, especially where there are large quantities of individual designs involved to warrant the development of the best electrical con-figuration and epoxy formulation for a given set of conditions.

There are two basic problems involved:

1. Corona: It is extremely difficult to obtain consistent, good, impregnation in each unit so that corona is likely to be present at voltages somewhere above 10 KV. This statement can be contra-dicted in many instances where there has been a good design of electrode configuration in the transformer, the casting process is fully developed, and the epoxy itself is ideally tailored for the particular application. For the most part, however, this basic problem keeps cropping up and it is very difficult to handle due to the fact that once cast, the unit cannot be dissected very well or salvaged.

2. Mechanical Properties: Several of the properties desired of an epoxy potting material are contradictory in nature requiring compromise on the part of the formulator:

   A. Molecular Rigidity: A high degree of crosslinking or molecular stiffness is required for good high temperature properties such as dissipation factor and heat distortion temperature. On the other hand, this stiffness results in a tendency to crack at low temperatures (-50 C) when a large mass of copper such as a coil is imbedded in the epoxy. Admittedly, there are excellent compromises for this problem possible and available commercially, but each one has to be evaluated completely for a specific application.

   B. Viscosity and Thermal Expansion: The conventional way to limit the coefficient of expansion of an epoxy is to increase the content of low expansion filler materials. Unfortunately, this results in increased casting viscosity which, in turn, increases the possibility of incomplete impregnation and resultant internal corona. Again, there are excellent

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compromises and new techniques available which
decrease this problem, but the chance of trouble from
corona or cracking is too prevalent to allow the use of
epoxy impregnation above voltage levels of about 10 KV
operating and for the complete range of temperature
from MIL-E-16400 class 1 cold spot to 200 C hot spot.
References: 100 and many others too numerous to list.

M. Silicone Rubber Potted: If the light weight of a dry type unit is still
desired in spite of the potential pitfalls of a varnished dry type or epoxy
potted transformer, the use of silicone rubber for impregnation and
potting will eliminate some of the above mentioned problems. When
properly cured, a silicone rubber should withstand -60 C to + 250 C
temperatures with no chance of cracking or premature degradation.
However, the possibility of corona due to incompletely filled voids
next to internal electrodes is just about as prevalent as it is with epoxy.
Therefore, the use of this system is also restricted to below about 10KV
operating. References: 2, 3, 8, 48, 100

A list of most of the above insulations and their comparative properties
is shown in table III.

MAJOR INSULATIONS TO BE INVESTIGATED:

It is felt that three of the thirteen insulation systems mentioned are beyond the
intended scope of this contract. These are: (1) air insulated dry type, (2)
silicone rubber impregnated, and (3) epoxy impregnated. The electrical design
using these three major insulations would be similar to that with the
other major insulations and, therefore, would be applicable with only minor
adjustments if one of these were used. Since these three insulations are listed
as secondary possibilities in table 1, and since they are restricted to low
voltage and power, it is felt that only cursory mention of them is in order
for this contract.

Of the remaining 10 insulations, the use of transil and askarel oil is well
documented in text books. The use of gas anf fluoroliquid evaporative cooling
and fluoroliquids themselves have been investigated by others. References:
1, 11, 20, 21, 25, 31, 46, 47.

The gases SF_6, C_3F_8, and $C-C_4F_8$ gas are limited by temperature restrictions.
This leaves C_2F_6 gas and the silicone liquids as obvious choices for the most
additional work under the contract.

The C_2F_6 requires investigation of its dielectric and thermal properties. To
date, this gas has not been studied as much as the others because of its slightly
lower dielectric strength. This does not mean that time will be spent learning
non-applicable facts about this material. Instead, the investigation will be
aimed at determining more applicable design factors such as the corona

starting voltage of typical uniform and non-uniform fields encountered in every transformer design. In addition, the thermal calculations for transformers using this and other gases need to be broadened, simplified, and verified.

The silicone fluids need substantiation of their electrical properties, especially the combination with various sophisticated, inert, filler materials which could substantially reduce the cost. As with the gas, the thermal calculation methods will also be verified.

One other area which is open to discussion is the high temperature limitations of SF_6. If this gas were proven acceptable for 10,000 hour military life with a 200 C hot spot, it could be the ideal gas for use in military electronic equipment. The determination of this, however, is considered beyond the contract scope. The above areas are where additional development work will be done on major insulation. Of course, design parameters for all ten of the major insulations within the scope of the contract will be included in the interim and final reports.

LAYER, BARRIER, AND FORM INSULATION

These insulations are all solid dielectrics and are often similar in material makeup, although they are used in different places. The primary difference between the three is thickness and flexibility. A good barrier insulation should be flexible to allow its bending over the ends of coils, cores, etc., whereas, a good form insulation needs to be stiff and strong for mechanical support.

For the purposes of this contract, these three solid insulations will be grouped according to hot spot temperature use -(that is 105 C, 130 C or 200 C). This means that any solid insulation of a temperature group may be used in its temperature range regardless of the type of major insulation used. This is only a general rule as each solid insulation should be thoroughly examined for its compatibility both chemically and electrically for each application. For the most part, these temperature classifications will coincide with the same numerical transformer hot spot groups covered in contract, but it is possible for a solid insulation to be used in some area in the transformer where it will be substantially cooler than the transformer hot spot, and therefore, only have to be of lower temperature classification.

Reference should be made here to the AIEE standard classification of insulation materials since the temperature classes as grouped in the contract are nearly the same and can be treated the same as the standard equivalent AIEE classes. These classes are shown in table IV as listed by AIEE with several comments added by the writer. Further elaboration on table IV is as follows:

Class A (105 C): Materials in this class are traditionally cellulosic, although the use of certain inexpensive varnishes renders inorganic filler

materials suitable only for class A use. The following list includes the usual class A solid materials:

    Papers
    Pressboard
    Wood
    Chipped wood products
    Cotton products
    Silk products
    Glass or inorganic products using class A varnishes
    Vulcanized fibre products
    Linen products (cambric)
    Paper and cotton phenolic or epoxy laminates.

Class B (130 C): This class is made up of non-cellulosic materials as far as AIEE is concerned but for purposes of this contract, it includes the uprated papers which will satisfy class B temperatures for shorter lifes. Solid materials in this class would be:

    Uprated cellulosic paper
    Uprated cellulosic pressboard
    Asbestos products ⎫
    Mica products   ⎬ with class B varnishes
    Glass products   ⎭
    Dacron
    Mylar
    Other polyester films and products

A further discussion of the need for chemically modified or uprated papers is included in a later section on turn insulation.

Class H (180 C AIEE, 200 C Navy): The predominate material in this class is the silicone family. The silicones are available as elastomers or varnishes with or without inorganic backing of fiberglas, asbestos or mica. A complete list would be:

    Silicone elastomer
    Asbestos products ⎫
    Mica products   ⎬ with silicone binder or with no binders
    Glass products   ⎭
    Glass with class H polyester varnish
    Teflon product ⎫
    HT-1 products   ⎬ new duPont polymers
    ML products   ⎭
    Kodar - new Eastman Kodak polymer -(Not proven as yet, but worthy
                                            of consideration)

It should be stated at this point that in all three temperature classes, there are new materials presently under development but which are not yet ready or available for general use.

SOLID INSULATIONS TO BE INVESTIGATED

Of the wide variety of solid insulations mentioned (other than turn insulation and varnishes which will be discussed later), only a few warrant additional investigation within the scope of the contract. These will be needed for use with the high temperature major insulations that are to be evaluated (C_2F_6, SF_6, silicone fluids). A final selection of the solids to be used in the verification units will be delayed pending the outcome of further interim work. Those to be used for interim work will be:

> Glass silicone laminate (NEMA G-7)
> Glass silicone layer insulation
> Polyester-glass layer insulation
> Asbestos silicone
> Kodar

The reason for selecting the above materials is that they combine the desired properties with the lowest cost for class H use. It may, however, be necessary to use the more expensive teflon in some applications if its low dielectric constant is required.

The kodar is a new terephthalate polyester film produced by the Eastman Kodak Company. It is an unevaluated material which may be very good for class H transformer use. It will be evaluated under the contract since it appears to combine the properties desired for a gas insulated transformer layer insulation.

TURN INSULATION

The turn insulations discussed here will only be those applied as a liquid film, although it is possible to insulate metal conductors with most of the solid insulations listed above.

There are many factors to consider before selecting an enamel. Some of these are as follows:

1. Life desired at hot spot temperature.

2. Compatability with other insulation components (resistance to chemical action).

3. Dielectric properties:
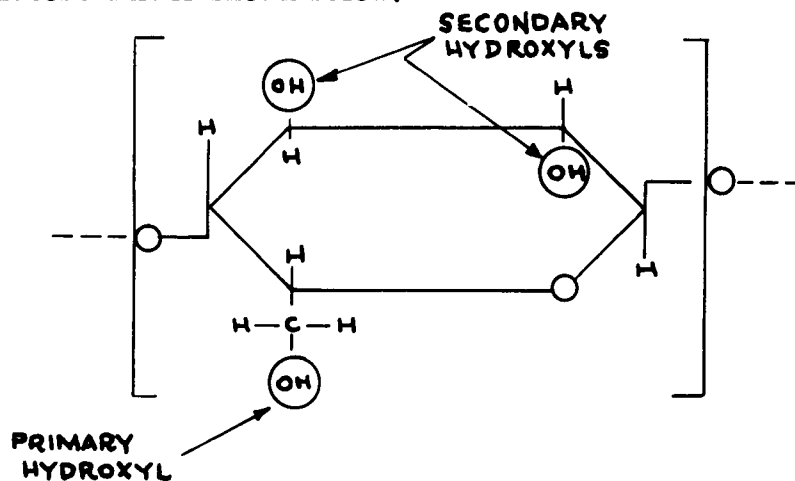
> a. Dielectric strength

b. Dissipation factor

c. Dielectric constant

4. Mechanical properties

a. Flexibility

b. Resistance to abrasion

c. Cut-through resistance

d. Heat shock resistance

e. These same properties after aging

The long term compatibility of wire enamels with other materials in the transformer has been the source of much grief and many failures since the first transformers were made. It cannot be stressed enough that any wire enamel used should be completely evaluated with the other materials it will be used with and that the subsequent substitution of just one of the other materials might have a dire effect on the chemical stability of the whole system.

The best example of this problem is the wide difference in sensitivety to hydrolysis exhibited by the different enamels. The presence of unmodified cellulose in a paper-oil-enamel system will, after time and heat, result in the formation of H_2O (water). This water plus CO_2 are formed by the deterioration of the glucose units which make up cellulose chain structure. A single glucose unit is shown below:

The hydroxyl units shown form the water which is so damaging to the other organic materials in the system. The action of this liberated moisture on the wire enamel in a sealed system can drastically affect its properties. The dielectric strength and mechanical properties of the enamel (and of the paper as well) are reduced to practically nothing and failure of the unit ensues. This is the primary reason for the use of chemically modified papers in higher temperature, modern transformers and in some cases, is good reason for not using cellulosic insulation at all. An example of chemical modification of the paper is the substitution of acrylic nitile groups for some of the less stable, water forming hydroxyl groups resulting in cyanoethylation of the paper. Discussions of this subject can be found in references 32, 33, 34, 35, 38, 75, 77, 101.

Like the other insulation components, the simplest way to categorize the wire enamels is by hot spot temperature. The most common enamels are:

Class A

Acrylic: MIL-W-583B not applicable	Predominately used with refrigerants. Limited by temperature and stress cracking.
Nylon: MIL-W-583B class 105 type T, T2, T3, T4	Used in small transformers where windability or solderability is important. Limited by cut through and by hydrolysis susceptibility. It also has low resistivity.
Oleoresinous (plain): MIL-W-583B class 105, Type E,E2	Inexpensive, very common, possibly used with askarels for class A use only.
Phenolic Modified: **Polyvinyl Formal:** MIL-W-583B Class 105, type T, T2, T3, T4	Most common enamel, very resistant to hydrolysis. Very tough. May be used for 10,000 hour class B applications with chemically modified Kraft.
Polyurethane: MIL-W-583B not applicable	Used for class A applications where solderability is required. Susceptible to hydrolysis.

Class B

Epoxy: MIL-W-583B Class 130 Type B, B2, B3, B4	Excellent for sealed transformers. Very resistant to hydrolysis. Possibly used in askarels.
Polyester: MIL-W-583B Class 130 & 155 Types B, B2, B3, B4, L, L2, L3, L4	Various modifications of the material are also suitable for 155 C (AIEE class F) use. Very resistant to temperature but susceptible to hydrolysis.

Class H

Polyimide (ML): MIL-W-583B Class 200, Type K, K2, K3, K4	Outstanding thermal and cutthrough resistance. Susceptible to hydrolysis. Possibly used in askarels.

<u>Teflon:</u>   Poor scrape abrasion and cut through resistance.
MIL-W-583B
Class 200
Type K, K2, K3, K4

It should be noted that the above enamels are only the basic materials and there are many combinations or modifications of these with widely varying properties. For the most part, however, the comments above are the most important considerations and hold true for the outermost layer when the film is made up of multiple enamels.

TURN INSULATIONS TO BE INVESTIGATED

From the preceeding discussion, it can be seen that the subject of turn insulation using film applied materials is an extensive subject by itself. For this reason, the turn insulations used for the contract investigation will be limited to common polyvinyl formal for the class A and class B - 10,000 hour applications and to ML for the 200° class H application. In addition, some of the industry-wide inconsistency in selection of enamels for use with askarels will be clarified.

If there is need for large rectangular turn conductor in the high power range of the contract, it is likely that additional lapped paper insulation may be used for class A and class B - 10,000 hour use (uprated lapped paper for class B) and that glass-silicone turn insulation may be used for the class H 200 C transformers.

VARNISHES

The sixth and final form of insulation may or may not be used in transformers. Varnish is a necessity for air insulated units to protect against moisture and contamination and to improve the dielectric strength. It is infrequently used in liquid filled transformers except when additional mechanical strength of the structure is required. Its infrequent use is because of the tendency for the hardened varnish to trap air in bubbles which will lead to early failure.and in some cases because its properties are not required.
For sealed gas insulated transformers, varnish use is also to be carefully scrutinized because of the possibility of trapped air although because of the equality in dielectric constants of dielectric gas and plain air, there is much less chance of corona and electrical failure.

Like the other five forms of insulation in this discussion, the topic of varnishes is an extensive science by itself. The general rule, however, that long-time chemical compatibility between this and the other components in the system should be thoroughly evaluated still holds true. Rather than describe all the

available varnishes in detail, the reader is referred to reference #56 for a comprehensive discussion on the subject.

The similarity between the varnishes and the turn insulation is apparent and most of the comments on the various insulations hold true for the similar varnishes. The problems of hydrolysis and temperature are usually not quite as severe with varnishes because they are not by function directly in contact with copper wire in the hottest spots in the transformer.

VARNISHES TO BE INVESTIGATED

Due to the fact that the contract involves fairly high voltages, and for the most part, favors sealed liquid or gas transformers, it is unlikely that varnish coating will be used. Another reason for the absence of varnish is that the transforme rs involved are not of the type which would be expected to survive high short circuit stresses. The only possible reason for varnish for the verification units might be for mechanical strength, especially of the units are gas filled. The varnish in this case would be a class H silicone providing compatibility test results are acceptable.

GAS VERSUS LIQUID

One of the major questions which arose during this preliminary investigation was whether to use gas or liquid as the major insulation in the final verification units. This question can never be accurately answered without considering the exact combination of specifications the transformer has to satisfy.

The general question, however, has come up time and time again and will continue in the future, especially when the final decision as to what to use in each verification unit has to be made. Table I is an attempt to clarify the situation, but since there are many combination blocks where both gas and liquid major insulations are mentioned, it is felt that further discussion of this question is in order. A careful examination of the following comments which compare the advantages and disadvantages of liquid and gas major insulations should help in the decision.

1. **Cost**
    Air as a gas is, of course, the least expensive major insulation. This means that whenever a unit can be of varnished dry type construction, it should be. However, this is not the case for most higher voltage military transformers. Air and open construction are not dependable enough for many of the service conditions and voltages encountered.

    The next logical choice is transil oil which is the best combination of properties for the cost of any major insulation. It is, however, flammable, heavy, and limited to class A and B temperatures.

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The third choice if transil oil cannot be used is a fluorogas which will be substantially lighter and less costly than an askarel.

The fourth choice would be an askarel if the power density (cooling) and voltage are too much for a fluorogas.

The fifth choice if the power density (cooling) is too much for a gas, but the voltage is not, would be a fluorogas - fluorovapor system. This system would probably be more costly than an askarel system although there may be examples where it is not.

Sixth and only if the temperature is too high for an askarel and the voltage too high for fluorgases should the very expensive silicone or fluoroliquids be used. Since these materials range from 20 to over 300 dollars per gallon, their use in a large transformer can only be justified by very unusual combinations of requirements.

2. Operating Temperature Range

Air is the best choice since it has no limitations in this respect except for its effect on other materials in the unit.
The silicone liquids also can be used over the complete ambient temperature range expected within the scope of the contract.

The fluorocarbon gases are the next choice although their low temperature limitations are restricted by their boiling points. Only one - C_2F_6 is satisfactory for the entire range. SF_6 has a low enough boiling point but may be susceptible to excessive breakdown and reaction with other transformer materials above 150 C.

Transil oil is limited to 145 C by flashpoint although it is conceivable that this temperature might be exceeded in a completely sealed transformer with no oxygen present.

Askarels are limited by excessive dissipation factor to 130 C - 10,000 hour life and even this use requires careful limiting of the other materials used in the system.

The fluoroliquids are limited to their boiling points which are 105 and 177 C for the two discussed. Usage above these temperatures requires elaborate provision for pressure increase.

3. Weight

At first thought, it will appear obvious that gases are completely favorable in this respect. But, in some cases, due to voltage and heat dissipation the unit has to be so much larger that the weight savings is lost.

4. Size
   A liquid filled unit is usually smaller than an equivalent gas unit,
   although an untanked dry type (air insulated) is sometimes the smallest
   of all. If careful design and evaporative cooling is used, it may be
   possible to make a gas filled unit as small as a liquid unit of the same
   rating.

5. Flammability
   The fluoroliquids and fluorogases are completely non-flammable. The
   askarels are non-flammable. The silicone fluids have varying degrees
   of flammability providing the flashpoint is exceeded. This flashpoint is
   very high which makes the silicone fluids exceedingly hard to ignite.
   For some applications, they may be considered non-flammable.

   Transil oil, because it is a mixture of aliphatic and aromatic hydrocarbons
   must be considered highly flammable.

6. Other Comparisons
   Other advantages of gas over liquid filling are as follows:

   The gas is explosion proof, meaning that an internal failure cannot
   transmit a rapid pressure rise to the tank wall through a compressible
   gas.

   With gas and proper mechanical mounting, the gas insulated transformer
   can be much quieter than a corresponding liquid filled unit due to the
   compressibility of the gas.

   Major insulation handling is simplified since many cubic feet of gas can
   be stored in a few small cylinders.

SUMMARY

The conclusions of this preliminary literature review and preceeding discussion
are as follows:

1. In order to properly satisfy every condition combination expected within
   the scope of the contract, many different insulation materials with
   widely varying properties would have to be used.

2. Most of the insulation materials are presently in use and their use is
   well documented. Only compilation and organization of this information
   will be done for the contract.

3. Several new materials and combinations of materials would seem to
   provide an excellent compromise of desired properties. These will
   be investigated further and reported in more detail.

4. Hexafluorothene, C_2F_6 gas needs to be more thoroughly investigated for military use due to its inertness and wide operating temperature range.

5. Silicone fluids, especially with inert, high quality, inexpensive filler materials need to be investigated further for use in high temperature audio transformers.

6. The verification units will be constructed, using for major insulation one of the two materials mentioned in 4 or 5 above. The exact material used, and whether or not additional cooling such as evaporative or forced convection will be used will be determined after additional investigation.

TABLE 1

MIL-E-16400				Flammable Major Insulation Allowed			Non-Flammable Major Insulation		
Hot Spot / Insulation / Voltage				Class 1 & 3	Class 2	Class 4	Class 1 & 3	Class 2	Class 4
200 C Hot Spot	LP-WF	HV		M-C-F	M-C-E	M-C-D	C-F	C-E	C-D
		LV		J-F	J-E	J-D	K-F	K-E	K-D
	HP-NF	HV		C-F-M	C-E-M	C-D-M	C-F	C-E	C-D
		LV		F-J	E-J	D-J	F-K	E-K	D-K
Hot Spot 130 C	LP-WF	HV		A-L-C	A-L-C	A-L-C	B-H-I-C	B-H-I-C	B-H-I-C
		LV		A	A	A	B-I-H	B-I-H	B-I-H
	HP-NF	HV		C-A-L	C-A-L	C-A-L	C-L-G-B	C-L-G-B	C-L-G-B
		LV		A	A	A	G-B-I	G-B-I	G-B-I
Hot Spot 105 C	LP-WF	HV		A-L-C	A-L-C	A-L-C	B-L-C	B-L-C	B-L-C
		LV		A	A	A	B	B	B
	HP-NF	HV		C-A-L	C-A-L	C-A-L	C-B-L	C-B-L	C-B-L
		LV		A	A	A	B	B	B

SEE TABLE 2 FOR EXPLANATION OF TABLE SYMBOLS

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TABLE 2

CODE FOR TABLE 1

A = Transil oil

B = Askarel oil

C = Air insulated dry type (varnished)

D = C_4F_8 gas ins.

E = C_3F_8 gas ins.

F = C_2F_6 gas ins.

G = SF_6 gas ins.

H = Gas and fluoroliquid evaporative cooling.

I = Fluoroliquid

J = Silicone fluid

K = Sil-phenylene liquid

L = Epoxy impregnated

M = Silicone rubber impregnated

LP = Low power

WF = Wide frequency

HP = High power

NF = Narrow frequency

HV = High voltage

LV = Low voltage

NOTE: There are some instances where non-flammable insulation is
mentioned where flammable insulation is allowed. This is done
when these non-flammable insulations would be a good choice
for the combination of considerations.

TABLE 3

PROPERTIES OF MAJOR INSULATIONS

EXCLUDING: C_4F_8

SIL-PHENYLENE LIQUIDS

GAS WITH FLUOROLIQUID EVAPORATIVE COOLING

PROPERTIES			
	IMPORTANT DISADVANTAGES	IMPORTANT ADVANTAGES	EXTENT USED TODAY IN TRANSFORMERS
EPOXY IMPREGNANT (TYPICAL)	LIMITED IN VOLTAGE TO 15KV. DIFFICULT TO IMPREGNATE CONSISTENTLY	LESS EXPENSIVE THAN RTV GOOD DIEL.STRENGTH	RUGGEDIZED DRY TYPE
SILICONE RTV-60 RUBBER	LIMITED IN VOLTAGE TO 15KV OPER. HIGH COST	GOOD MECH. & THERMAL STABILITY	HIGH TEMP., HIGH VOLTAGE DRY TYPE
FC-43 OIL	EXTREMELY HIGH COST	NON-FLAMMABLE, EXC.DIEL. STRENGTH SELF-HEALING	USE IN SMALL ELECTRONIC
FC-75 OIL	VERY HIGH COST, SENSITIVE TO PURITY, REQUIRES GAS CUSHION	NON-FLAMMABLE, LOW BOIL-ING POINT FOR VAPOR COOL-ING EXC.DIEL.STRENGTH	USED IN SMALL ELECTRO-NIC & SOME VAPOR COOLED POWER
GE SF97(20) SILICONE OIL	S. FLAMMABLE, HIGH COST, SENSITIVE TO ARC CONTAMINATION	VERY STABLE, HIGH DIELECTRIC STRENGTH	USED IN SMALL HIGH-TEMPERATURE
ASKAREL OIL	HIGH DISSIPATION FACTOR AT MEDIUM TEMPERATURES SUSCEPTIBLE TO CONTAMINATION	NON-FLAMMABLE HIGH DIELECTRIC STRENGTH	USED IN NON-FLAMMABLE HIGH VOLTAGE
TRANSIL OIL	FLAMMABLE OXIDIZES	VERY INEXPENSIVE. VERY GOOD DIELECTRIC STRENGTH AND COOLING	USED IN MOST HIGH VOLTAGE
C_2F_6	DIEL. STRENGTH SLIGHTLY LOWER THAN C_3F_8 OR SF_6	INEXPENSIVE HIGHER DIEL-ECTRIC STR.THAN AIR. LOW BOILING POINT.	NOT USED YET
SF_6	NOT STABLE WITH SIL.STEEL ABOVE 150°C	INEXPENSIVE HIGHER DIELECTRIC STR.THAN AIR	SOME POWER & ELECTRONIC
C_3F_8	BOILING POINT TOO HIGH FOR MIL USE IN EXTREME TEMPERATURES	INEXPENSIVE STABLE HIGHER DIELECTRIC STR. THAN AIR	SOME MEDIUM POWER
NITROGEN	LOW DIEL. STRENGTH	INEXPENSIVE INERT	LOW VOLTAGE DRY TYPE
AIR	OXIDIZES OTHER COMPONENTS LOW DIEL. STRENGTH	INEXPENSIVE	LOW VOLTAGE DRY TYPE

PROPERTIES	AIR	NITROGEN	C_3F_8	SF_6	C_2F_6	TRANSIL OIL	ASKAREL OIL	GE SF97(20) SILICONE OIL	FC-75 OIL	FC-43 OIL	SILICONE RTV-60 RUBBER	EPOXY IMPREGNANT (TYPICAL)
(1) Cost $/Pound	0	0.21	9.00	2.50	7.50	0.037	0.132	2.63	7.50	20.00	4.35	1.50
(2) Cost $/Gallon	0	0.002	0.63	0.13	0.38	0.27	1.72	21.00	110.00	310.00	52.00	19.00
(3) Specific Gravity 25°C 1 ATM	0.00129	0.00124	0.0083	0.0065	0.0057	0.885	1.56	0.964	1.77	1.87	1.47	1.50
(4) Weight Pounds 25°C 1ATM GAL.	0.0107	0.0104	0.07	0.052	0.0515	7.3	13.0	8.0	14.7	15.5	12.0	12.6
(5) Viscosity Centi-Poises 25°C	.018	.018	.0178	.0157	.0145	14	6.5	19.2	1.43	5.1	SOLID	SOLID
(6) Viscosity Centi-Poises 100°C	.021	.021	.020	.0197	.017	3.5	3.0	5.7	0.43	0.93	SOLID	SOLID
(7) Specific Heat(C_p) 25°C BTU/#°F	0.24	0.25	0.192	0.158	0.19	0.425	0.255	0.36	0.25	0.27		
(8) Specific Heat(C_p) 150°C BTU/#°F	0.24	0.252	0.228	0.194	0.22	0.53		0.51	0.236			
(9) Thermal Cond. $\frac{WATT}{cm°C}$ 25°C	.00066	.00071	.00038	.00036	.00042	.0034	.0032	0.0036	0.0036	0.00215	0.008	
(10) Coef.Volume Exp. 25°C $\frac{1}{°C}$	GAS LAW	GAS LAW	GAS LAW	GAS LAW	GAS LAW	.00074	.00067	.00094	.0016	.0012	.0003	.0003
(11) Coef.Volume Exp. 150°C $\frac{1}{°C}$	GAS LAW	GAS LAW	GAS LAW	GAS LAW	GAS LAW	.00073	.0006	.009945	.002	.0021		
(12) Molecular Weight	28.95	28.01	188.02	146.06	138.0	-	-	-	-	-	-	-
(13) Freezing Point °C 1 ATM		-209.8	-160	-50.8	-101				-113	-66	-	-
(14) Boiling Point °C 1 ATM	-194	-195.8	-36.7	-63.8	-78.2			270°C START	105	170	-	-

PROPERTIES	AIR	NITROGEN	C₃F₈	SF₆	C₂F₆	TRANSIL OIL	ASKAREL OIL	GE SF97(20) SILICONE OIL	FC-75 OIL	FC-43 OIL	SILICONE RTV-60 RUBBER	EPOXY IMPREGNANT (TYPICAL)
(15) MAX. OPERATING TEMPERATURE °C	300+	300+	275	150+	300	130	130	400	VAPORIZE 400	200	300	150
(16) MIN. OPERATING TEMPERATURE °C	-150	-150	-30	-55	-60	-50	-50	-80	-50	-50	-65	-60
(17) FLAMMABLE	No	No	No	No	No	Yes	No	(BARELY) Yes	No	No	(BARELY) Yes	Yes
(18) FLASH POINT	-	-	-	-	-	145°C	-	275°	-	-	-	-
(19) TOXIC	No	No	No	No	No	No	SKIN IRRITANT	No	No	No	No	No
(20) DIELECTRIC STRENGTH $\frac{RMS\ V}{MIL}$ 25°C, 1ATM, 60~, FIELD UNIFORM	50	60	100	110	90	350	350	350	370	400	370	300
(21) DIELECTRIC STRENGTH $\frac{RMS\ V}{MIL}$ 25°C, 2ATM, 60~ UNIFORM FIELD	100	120	200	220	180	420	420	420	370+	400+	370	300
(22) DIELECTRIC CONSTANT 25°C, 60~	1.0	1.0	1.0	1.0	1.0	2.2	4.0	2.7	1.84	1.89	4.0	3.5
(23) DISSIPATION FACTOR 25°C, 60~	-	-	-	-	-	.0001	.003	.0001	.0005	.0005	.020	VARIES WIDELY
(24) POUR POINT °C	-	-	-	-	-	-45°	-40	-76	-100	-50	-	-
(25) RESISTANCE TO ARCOVER CONTAMINATION	GOOD	GOOD	GOOD	GOOD	GOOD	BAD	BAD	BAD	GOOD	GOOD	GOOD	BAD

TABLE 4

TEMPERATURE CLASSES OF MATERIALS

AIEE #1 Temp. Hot Spot	Similar AIEE Class For Refer.	Contract (Navy) Temp. Hot Spot	Description
105°C	A	105°C	Materials or combinations of materials such as cotton, silk, and paper when suitably impregnated or coated or when immersed in a dielectric liquid such as oil. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to be capable of operation at 105°C.
130°C	B	130°C	Materials or combinations of materials such as mica, glass fiber, asbestos, etc. with suitable bonding surfaces. Other materials or combinations of materials not necessarily inorganic may be included in this class if by experience or accepted tests they can be shown to be capable of operation at 130°C. The uprated Kraft papers and boards are the best examples of a material of this type. These uprated cellulosic materials can be considered 130°C material for 10,000 hour life but are not quite AIEE class B materials which should have longer lifes of 20 years.
180°C	H	200°C	Materials or combinations of materials such as silicone, mica, glass fibre, asbestos, teflon and other fluorochemicals. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to be capable of operation at 180°C for 20 years or 10,000 hours at 200°C.

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EXHIBIT 2

MILESTONE REPORT #3

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

WINDING ARRANGEMENTS USED IN HIGH POWER AUDIO FREQUENCY TRANSFORMERS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NOBSR 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ⬤ ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

DEFINITION OF SYMBOLS

A - Square inches - Leakage area

b - Inches - Half wave length of mmf diagram

C_d - Picofarads - Distributed capacitance

d - Inches - Bare wire diameter

D - Inches - Total winding build

E - Volts - RMS voltage of base winding

h - Inches - Length of winding traverse

I - Amperes - RMS current

K -   - Dielectric constant of the insulation of the capacitor electrodes

K_r -   - Rogowski correction factor

ℓ - Inches - Mean length of turn

L_L - Henries - Leakage inductance

m -   - Number of layers in winding

N -   - Number of turns in winding

S - Inches - Insulation thickness

V - Volts - RMS voltage of winding or winding section

The use of subscripts in the equations of leakage inductance and distributed capacitance for the various winding arrangements is defined by the following example:
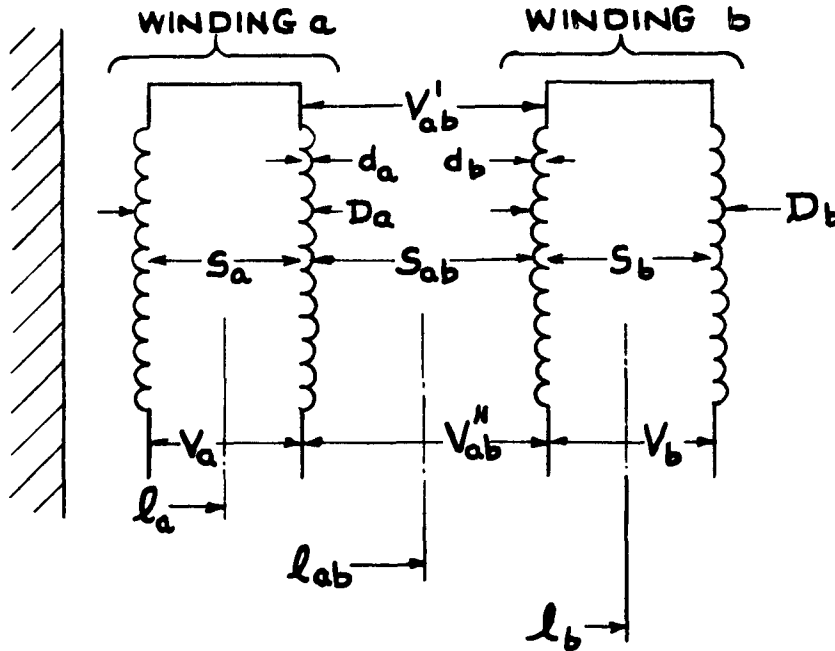
where:

ℓ_a - mean length of winding a

ℓ_{ab} - mean length of space between winding a and winding b

ℓ_b - mean length of winding b

S_a - insulation thickness between layers of winding a including wire insulation.

S_{ab} - insulation thickness between winding a and winding b including wire insulation.

S_b - insulation thickness between layers of winding b. including wire insulation.

d_a - bare wire diameter of winding a

d_b - bare wire diameter of winding b

D_a - total build of winding a

D_b - total build of winding b

V'_{ab} - RMS voltage between winding a and winding b at one end of winding traverse.

V''_{ab} - RMS voltage between winding a and winding b at the other end of winding traverse.

V_a - RMS voltage of winding a

V_b - RMS voltage of winding b

The purpose of this report is to show some of the winding arrange-
ments used in wide band or high frequency transformers, and to give
their associated equations for leakage inductance and distributed ca-
pacitance. A sample derivation is included to clarify the use of the
equations derived in exhibit I of the First Quarterly Report as is a
sample calculation. A tabulation of values measured on model coils and
their calculated value is given to check the accuracy of the equations.

A detailed discussion on the selection of a particular winding arrange-
ment for a given application is not practical at this time because it
involves the frequency response requirements of the design, and the
copper losses. These are the subjects of milestone reports numbers
5 and 7.

A transformer that is to operate over a narrow high frequency band
must have a leakage inductance value low enough so that the inductive
reactance voltage drop (IX) does not cause excessively high regulation.
Some idea of the allowable magnitude can be obtained by noting that a
transformer having a 1% IX drop at 60 cps will have a 100% IX drop
at 6 KC.

A transformer that is to operate over a wide band of frequencies must
have predetermined values of leakage inductance, distributed capacitance,
and open circuit inductance, so that the circuit in which it is to be used
will have the desired frequency response. In general, the leakage
inductance and distributed capacitance must be made smaller, and the
open circuit inductance larger, as the band width is increased.

No attempt has been made to show all of the winding arrangements that
have been used in wide band or high frequency transformers. Rather,
arrangements have been selected which shown some of the methods which
have been devised to reduce the leakage inductance. No single arrange-
ment is best for all designs, so it is left to the transformer designer to
select one, or a combination of the ones shown or an arrangement of his
own design, that will meet his particular requirements.

Figure 1 shows a typical arrangement used for low frequency power
transformers. This arrangement would be used rarely in high frequency
transforme rs because of its high leakage inductance. It also would have
high copper loss, for reasons to be discussed in milestone report #7.
If one of the windings was divided into two equal sections, and the other
winding placed between the two sections, the copper losses would be
reduced, and the leakage inductance would be approximately halved.
This arrangement is shown in figure 2.

The output transformer of a push-pull amplifier requires a center tapped primary. To reduce distortion, the leakage inductance and distributed capacitance of each half primary to the secondary should be equal. The arrangement of figure 3 attempts to achieve this balance by splitting each half primary into two sections, and placing one section of each, above and below the secondary. Balance cannot be obtained unless sections 1 and 2 and sections 4 and 5 are interwound in the same winding layer. Even this does not provide perfect balance because the voltage gradient between sections 2 and 3 is not the same as the gradient between sections 3 and 4, which causes a difference in capacitance between half primaries and the secondary.

A better balance is obtained if both windings are divided into two equal sections, wound into separate coils, and placed on opposite core legs, as shown in figure 4. This arrangement also has some capacitance unbalance because of the different voltage gradients, as described above.

Another scheme devised to reduce the leakage inductance between half primaries is shown in figures 5 and 6. An electrostatic shield is added between each half primary section and the secondary. Each shield is an identical coil of one or more turns, and are connected so that the induced voltages are in series bucking. Because of the leakage flux, the voltage induced in each shield is not the same, so that there is a circulating current in the shields. This current sets up a flux which opposes and reduces the leakage flux, thus reducing the leakage inductance. These coupled shields are more fully described in United States Patent #2, 553, 324.

Another method devised to reduce the leakage inductance between half primaries is shown in figure 7. This arrangement is essentially two transformers utilizing the same core. One transformer consists of two half primary windings. With no secondary winding, the half primary windings can be interwound and tightly coupled. On the other leg, the second transformer consists of a primary and a secondary winding, again interwound and tightly coupled. Thus, one transformer gives low half primary to half primary leakage inductance, and the other from primary to secondary. This arrangement is further described by United States Patent #Re24,474.

An examination of the equations for leakage inductance and distributed capacitance will indicate what can be done to reduce the value of these parameters. From the First Quarterly Report, the equation for leakage inductance is:

$$L_L = \frac{3.19 \, N_s^2 \, (A_s + A_w) \, 10^{-8}}{h} \text{ Henries}$$

To change the leakage inductance, the most obvious change is in the number of turns, since this value is squared in the equation. However, as the turns are decreased, the core area must be increased to maintain the open circuit inductance and to prevent core saturation. The Rogowski correction factor is approximately one for most concentric windings and has no value in the control of the leakage inductance value. The winding traverse (h) can be used, and is especially effective, when it is necessary to change the L_L/C_D ratio, since (h) is in the numerator of one and the denominator of the other equation. The major control of leakage inductance is in controlling the effective leakage area $(A_s + A_w)$.

The leakage area of the space between windings is

$$A_s = \ell_s S \left[\frac{N_1 I_1}{N_s I_s} \right]^2 \text{ square inches}$$

where ($\ell_s S$) is the actual area of the space between the windings, at right angles to the leakage path, and $\dfrac{(N_1 I_1)}{(N_s I_s)}$ is the per unit mmf acting on this area. The mean length of the pad (ℓ_s) is usually fixed by the core area, but the thickness of the pad (S) can be reduced by increasing the voltage stress on the insulation and by arranging the windings so that the voltage across a pad is minimized. The per unit mmf on the pad is reduced by interleaving the winding. Note that a large duct or pad can be placed at any point where the mmf diagram goes through zero and the inductance will be affected only to the extent that the mean length of other sections are increased.

The leakage area of each winding or winding section is

$$A_w = \frac{\ell_1 d_1}{3} \left[\left(\frac{N_1 I_1}{N_s I_s} \right)^2 + \left(\frac{N_1 I_1}{N_s I_s} \right)\left(\frac{N_2 I_2}{N_s I_s} \right) + \left(\frac{N_2 I_2}{N_s I_s} \right)^2 \right] \text{ sq. in.}$$

Here $\dfrac{(N_1 I_1)}{(N_s I_s)}$ is the per unit mmf on one side of the winding layer and $\dfrac{(N_2 I_2)}{(N_s I_s)}$ is the per unit mmf on the other side, ℓ_1 is the mean length of turn and d_1 is the total copper radial build of the winding including all interlayer insulation in that coil. Here again, the turn length is fixed by the core area, but the coil build and the mmf on opposite sides of the coil is reduced by interleaving the coil sections.

The basic equation, shown in the First Quarterly Report, for distrib-
uted capacitance is:

$$C_D = \frac{C_{DC} \left[(V_1)^2 + (V_1 V_2) + (V_2)^2 \right]}{3 E_s^2} \; PF$$

where the DC capacitance (C_{DC}) between any two adjacent parallel plates,
or winding layers is:

$$C_{DC} = \frac{0.225 \; K \ell_1 h_1}{S_1}$$

Thus the DC capacitance can be decreased by reducing the dielectric
constant (K), the mean length ℓ_1, or by increasing the thickness (S_1) of
the insulation between windings, and by reducing the winding traverse (h_1).

The length (ℓ_1) of the insulation is fixed by the core area required. Any
attempt to alter the capacitance by changing (h_1) or (S_1) will cause a
proportional change in the leakage inductance in the opposite direction.
The dielectric constant is the only term that can be changed without
affecting the leakage inductance, and this is not easily changed.

Since the distributed capacitance (C_D) is a function of the voltage distrib-
ution, the method of interleaving greatly affects its value. For lower
distributed capacitance, the voltage difference between two windings at
opposite ends (V_1 and V_2) should be as low and as nearly equal as possible.

For the winding arrangements shown in figures 1 thru 7, equations for
leakage inductance and distributed capacitance have been derived and
are shown in the figures. To serve as a guide for the use of the basic
equations, the leakage inductance and distributed capacitance equations
for the winding arrangement shown in figure 4 are derived as follows:

From equation (8), exhibit 1 of the First Quarterly Report, the leakage
inductance is:

$$L_L = \frac{3.19 \; N_s^2 \; K_r}{h} (A_s + A_w) \; 10^{-8} \; \text{Henries}$$

where $A_g = A_1 \left(\dfrac{N_1 I_1}{N_s I_s}\right)^2 + A_2 \left(\dfrac{N_2 I_2}{N_s I_s}\right)^2 + \ldots + A_n \left(\dfrac{N_n I_n}{N_s I_s}\right)^2$

and $A_w = \ell_j d_j \left[\dfrac{(N_j I_j)^2 + (N_j I_j)(N_{j+1} I_{j+1}) + (N_{j+1} I_{j+1})^2}{3 (N_s I_s)^2}\right]$

Figure 4C shows the per unit mmf of 1/2 primary to 1/2 primary and 1/2 primary to secondary for the winding arrangement of figure 4.

Substitution in the above equations for the leakage inductance, 1/2 primary to 1/2 primary, is as follows:

$$A_g = \ell_{23} S_{23} (0.5)^2 + \ell_{45} S_{45} (0.5)^2$$

since coil I and coil II are identical, $\ell_{23} = \ell_{45}$ and $S_{23} = S_{45}$

$$A_g = (2)\ell_{23} S_{23} (0.5)^2 = \dfrac{\ell_{23} S_{23}}{2}$$

$$A_w = \dfrac{\ell_2 D_2 (0.5)^2}{3} + \dfrac{\ell_3 D_3 (0.5)^2}{3} + \dfrac{\ell_4 D_4 (0.5)^2}{3} + \dfrac{\ell_5 D_5 (0.5)^2}{3}$$

due to the symmetry of the coils, $\ell_2 = \ell_5$, $\ell_3 = \ell_4$ and $D_2 = D_3 = D_4 = D_5$

$$A_w = \dfrac{\ell_2 D_2}{6} + \dfrac{\ell_3 D_2}{6}$$

and since $\ell_2 + \ell_3 = 2\ell_{23}$

$$A_w = \dfrac{\ell_{23} D_2}{3}$$

The total leakage area (A) is the sum of A_g and A_w:

$$A = A_g + A_w = \dfrac{\ell_{23} S_{23}}{2} + \dfrac{\ell_{23} D_2}{3}$$

$$A = \ell_{23} \left[\dfrac{S_{23}}{2} + \dfrac{D_2}{3}\right]$$

To find the leakage area of 1/2 primary to secondary $(P_2 - P_{ct}$ to $S_1 - S_2)$:

$$A_s = \ell_{12}S_{12}\,(0.5)^2 + \ell_{46}S_{46}\,(0.5)^2$$

$$\text{since } \ell_{46}S_{46} = \ell_{13}S_{13}$$

$$A_s = \frac{\ell_{12}S_{12}}{4} + \frac{\ell_{13}S_{13}}{4}$$

$$A_w = \frac{\ell_1 D_1 (0.5)^2}{3} + \frac{\ell_2 D_2 (0.5)^2}{3} + \frac{\ell_4 D_4 (0.5)^2}{3} + \frac{\ell_6 D_6 (0.5)^2}{3}$$

since coil I and coil II are identical,

$$\ell_1 = \ell_6, \quad \ell_3 = \ell_4, \quad D_1 = D_6 \text{ and } D_2 = D_4$$

therefore $A_w = \dfrac{\ell_1 D_1}{6} + \dfrac{\ell_{23} D_2}{6}$

The total leakage area 1/2 primary to secondary is:

$$A = A_s + A_w = \frac{\ell_{12}S_{12}}{4} + \frac{\ell_{13}S_{13}}{4} + \frac{\ell_1 D_1}{6} + \frac{\ell_{23} D_2}{6}$$

From equation (8), page 8, of exhibit I, First Quarterly Report, the intra-winding capacitance of a winding i is given by the equation

$$C_{di} = \frac{0.30\ K_i \ell_i h_i}{S_i}\ \frac{(m_i - 1)}{m_i^2}\ \frac{V_i^2}{E_s^2}\ \text{PF}$$

Where E_s is the voltage base to which the capacitance is being referred.

This equation can be rewritten

$$C_{di} = \left[\frac{0.075\ h_i}{E_s^2}\right]\left[\frac{4\ell_i K_i\ (m_i - 1)(V_i)^2}{S_i\ m_i^2}\right]\ \text{PF}$$

Similarly, the interwinding capacitance, from equation (5), page 8, of the First Quarterly Report, of windings i and j is given by the equation

$$C_{dij} = \left[\frac{0.225\ K_{ij}\ell_{ij}\ h_{ij}}{S_{ij}}\right]\left[\frac{(V_{ij}')^2 + (V_{ij}')(V_{ij}'') + (V_{ij}'')^2}{3\ E_s^2}\right]\ \text{PF}$$

which can be rewritten

$$C_{dij} = \left[\frac{0.075\, h_{ij}}{E_s^2}\right] \left[\frac{\ell_{ij} K_{ij}}{S_{ij}} \left[(V_{ij}')^2 + (V_{ij}')(V_{ij}'') + (V_{ij}'')^2\right]\right] PF$$

For the winding arrangement of Fig. 4, considering the distributed capacitance of 1/2 primary to 1/2 primary, the intrawinding capacitance is zero since these are single layer windings. The interwinding capacitance 1/2 pri. to 1/2 pri. is

$$C_{d23} + C_{d45} = \left[\frac{0.075 h\, \ell_{23} K_{23}}{E_s^2 \quad S_{23}}\right]\left[(V_{23}')^2 + (V_{23}')(V_{23}'') + (V_{23}'')^2\right] (2)$$

Reference to fig. 4A shows that $V_{23}' = V_{23}'' = 2V_2$

$$C_d \ 1/2 \ pri. \ to \ 1/2 \ pri. = \left[\frac{0.075\, h\, \ell_{23} K_{23}}{E_s^2} \frac{}{S_{23}}\right] 24 V_2^2$$

$$= \frac{1.80\, h\, \ell_{23} K_{23} V_2^2}{E_s^2 \ S_{23}} \ PF$$

The distributed capacitance of the secondary winding is the sum of its intrawinding capacitance and interwinding capacitance

$$C_{dSEC} = \frac{0.075h}{E_s^2}\left[\frac{4\, \ell_1 K_1 (m_1-1) V_1^2}{S_1 m_1^2} (2) + \frac{\ell_{12} K_{12}(B_1)}{S_{12}} + \frac{\ell_{56} K_{56}(B_2)}{S_{56}}\right] PF$$

where $B_1 = (V_{12}')^2 + (V_{12}')(V_{12}'') + (V_{12}'')^2$

$B_2 = (V_{56}')^2 + (V_{56}')(V_{56}'') + (V_{56}'')^2$

since $\ell_{12} = \ell_{56}$, $S_{12} = S_{56}$ and $K_{12} = K_{56}$

$$C_{dSEC} = \frac{0.075h}{E_s^2}\left[\frac{8\, \ell_1 K_1 (m_1-1) V_1^2}{S_1 m_1^2} + \frac{\ell_{12} K_{12}}{S_{12}}(B_1 + B_2)\right] PF$$

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The use of these equations is demonstrated by the following calculations . They were made to obtain the leakage inductance and distributed capacitance of the model coil and to verify the equations derived above and shown in figure 4.

COIL DATA

	Primary	Secondary
Insulated wire diameter-inches	.029	.022
Bare wire diameter-inches	.025	.018
Wire insulation-inches	.004	.004
Turns per coil	200	400
Layers per coil	2	3
Turns per layer	100	133
Winding traverse-inches	3.08	3.08
Insulation between layers-inches	.030	.040
Winding form (round)	3" OD x 3.58" long	

To calculate the leakage inductance and distributed capacitance of a coil or set of coils, it is necessary to know the mean length of turn of the windings and of the insulation spaces between these windings. Figure 4B shows the radial build of coil I, and, since coil I and coil II are identical, this is also the radial build of coil II.

When calculating the distributed capacitance of a coil, it is also necessary to know the voltage distribution in the windings. The voltage distribution depends on which terminals are grounded and, for this example, terminals P_{CT} and S_2 are considered grounded. Figure 4A shows the voltage distribution for this case.

Radial Build and MLT's of Coil I

$$D_1 \begin{cases} \end{cases}$$

- 1.500 winding form
- .013 insulation
- 1.513 sub-total
- .018 secondary layer #1
- .048 interlayer insulation
- .009 1/2 secondary layer #2
- 1.588 sub-total $MLT\ell_1 = 2\pi\, 1.588" = 9.97"$
- .009 1/2 secondary layer #2
- .048 interlayer insulation
- .018 secondary layer #3
- 1.663 sub-total
- .057 1/2 interwinding insulation
- 1.720 sub-total $MLT\ell_{12} = 2\pi\, 1.720" = 10.80"$
- .057 1/2 interwinding insulation

$$D_2 \begin{cases} \end{cases}$$

- .013 1/2 primary layer #1
- 1.790 sub-total $MLT\ell_2 = 2\pi\, 1.790" = 11.24"$
- .012 1/2 primary layer #1
- .018 1/2 interlayer insulation
- 1.820 sub-total $MLT\ell_{23} = 2\pi\, 1.820" = 11.43"$
- .019 1/2 interlayer insulation
- 1.839 sub-total

$$D_3 \begin{cases} \end{cases}$$

- .013 1/2 primary layer #2
- 1.852 sub-total $MLT\ell_3 = 2\pi\, 1.852" = 11.63"$
- .012 1/2 primary layer #2
- 1.864 sub-total
- .035 insulation over coil
- 1.899 total build

In addition to the above MLT's, it is necessary to know the following:

$$S_{13} = 1.839 - 1.663 = .176"$$

$$MLT\ell_{13} = \left[1.663 + \frac{.176}{2}\right] 2\pi = 11.00"$$

$$D_q = 1.663 - 1.513 = .150"$$

Leakage Inductance 1/2 Primary to 1/2 Primary

$$L_L = \frac{3.19\, N_s^2\, K_r\, A\, 10^{-8}}{h} \quad \text{Henries}$$

$K_r = f$ (h/b) as outlined in exhibit 1 of the First Quarterly report.

$$b_{23} = .025 + .037 + .025 = .087"$$

$$h/b = \frac{3.08}{.087} = 35.4$$

From Fig. 7, exhibit 1 of the First Quarterly Report

when $h/b = 35.4$, $K_r \approx 1$

$$A = \ell_{23} \left(\frac{S_{23}}{2} + \frac{D_2}{3} \right) \text{ sq. in.}$$

$$= 11.43 \left(\frac{.037}{2} + \frac{.025}{3} \right) = .306 \text{ sq. in.}$$

$$L_L = \frac{3.19 \times (400)^2 \times 1 \times .306 \times 10^{-8}}{3.08} \text{ Henries}$$

$$L_L = .506 \text{ mhy} \quad \text{(referred to secondary)}$$

Leakage Inductance 1/2 Primary to Secondary

$$L_L = \frac{3.19 \ N_s^2 \ K_r \ A \ 10^{-8}}{h} \quad \text{Henries}$$

$$K_r = f \ (h/b), \quad b_{13} = 1.864 - 1.513 = .351"$$

$$h/b = \frac{3.08}{.351} = 8.8; \quad K_r = .96$$

$$A = \frac{\ell_{12}S_{12}}{4} + \frac{\ell_{13}S_{13}}{4} + \frac{\ell_1 D_1}{6} + \frac{\ell_{23}D_2}{6} \quad \text{sq. in.}$$

$$= \frac{10.80 \times .114}{4} + \frac{11.00 \times .176}{4} + \frac{9.97 \times .150}{6} + \frac{11.43 \times .025}{6}$$

$$= .308 + .484 + .250 + .048 = 1.090 \text{ sq. in.}$$

$$L_L = \frac{3.19 \times (400)^2 \times .96 \times 1.09 \times 10^{-8}}{3.08} \text{ Henries}$$

$$L_L = 1.74 \text{ mhy} \quad \text{(referred to secondary)}$$

This value of leakage inductance is the same for each half primary to secondary since the two coils are identical and the half primaries are symmetrical.

Distributed Capacitance 1/2 Primary to 1/2 Primary

$$C_{dp} = \frac{1.80\,h\,\ell_{23}K_{23}\,V_2^2}{S_{23}E_s^2}\ \text{PF}$$

Assume the dielectric constant K_{23} is 4.0

$$C_{dp} = \frac{1.80 \times 3.08 \times 11.43 \times 4.0 \times (-.25E_s)^2}{.037E_s^2}\ \text{PF}$$

$$C_{dp} = 428\ \text{PF}\quad \text{(referred to } E_s\text{)}$$

Distributed Capacitance - Secondary

$$C_{ds} = \frac{.075h}{E_s^2}\left[\frac{8\ell_1 K_1\,(m_1-1)\,V_1^2}{S_1\,m_1^2} + \frac{\ell_{12}K_{12}\,(B_1+B_2)}{S_{12}}\right]\ \text{PF}$$

$$B_1 = (V'_{12})^2 + (V'_{12})(V''_{12}) + (V''_{12})^2$$

$$= (.58E_s)^2 + (.58E_s)(0) + (0)^2$$

$$= .336\ E_s^2$$

$$B_2 = (V'_{56})^2 + (V'_{56})(V''_{56}) + (V''_{56})^2$$

$$= (.25E_s)^2 + (.25E_s)(.33E_s) + (.33E_s)^2$$

$$= .256\ E_s^2$$

$$C_{ds} = \frac{.075 \times 3.08}{E_s^2}\left[\frac{8 \times 9.97 \times 4.0 \times (3-1) \times E_s^2}{.048 \times 9}\right.$$

$$\left. + \frac{10.80 \times 4.0 \times (.336\ E_s^2 + .256\ E_s^2)}{.114}\right]\ \text{PF}$$

$$C_{ds} = 393\ \text{PF}\quad \text{(referred to } E_s\text{)}$$

To check the equations shown, model coils were wound and the leakage induction of each was measured. A comparison of the measured and calculated values are shown in figure 8.

A common method of measuring the distributed capacitance of pulse transformers is described in the "Instruction Manual for Preproduction Testing Under MIL-T-27 of Certain Transformers and Inductors", Contract No. DA-36-039-SC-30193 by Irving Richardson. The resonant frequency of the leakage inductance in parallel with the distributed capacitance and an external capacitor is measured with several different values of external capacitance. From this data, the leakage inductance and distributed capacitance can be calculated. When this method was used on the sample coils, a number of resonant frequencies were obtained for each value of added capacitance, making the results meaningless. A better method of measuring distributed capacitance will be investigated.
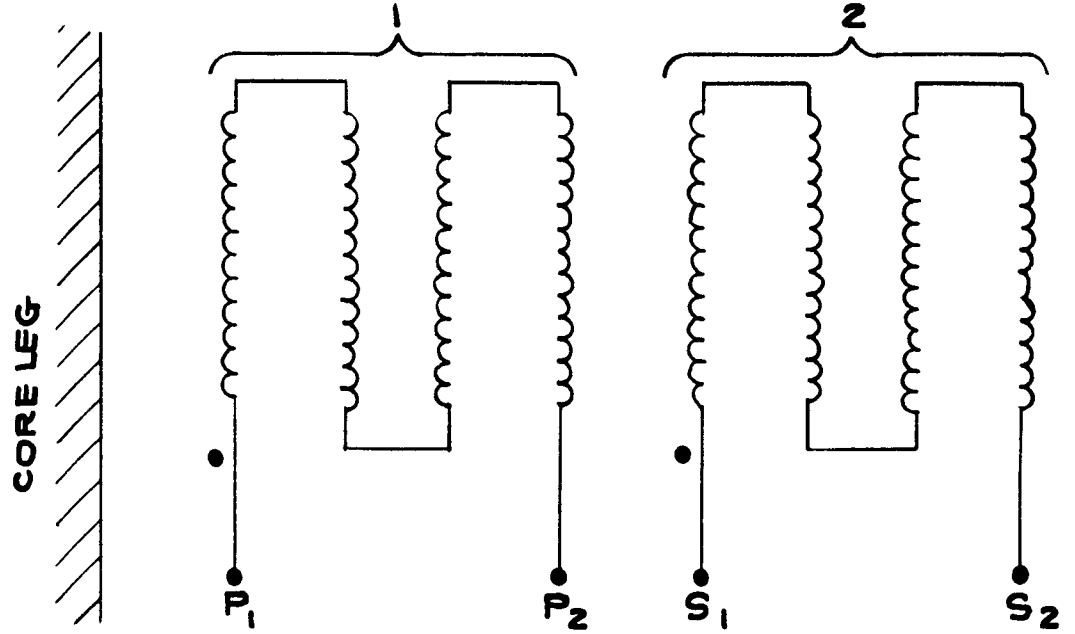
NOTES:

1. The winding traverse for all layers is the same.

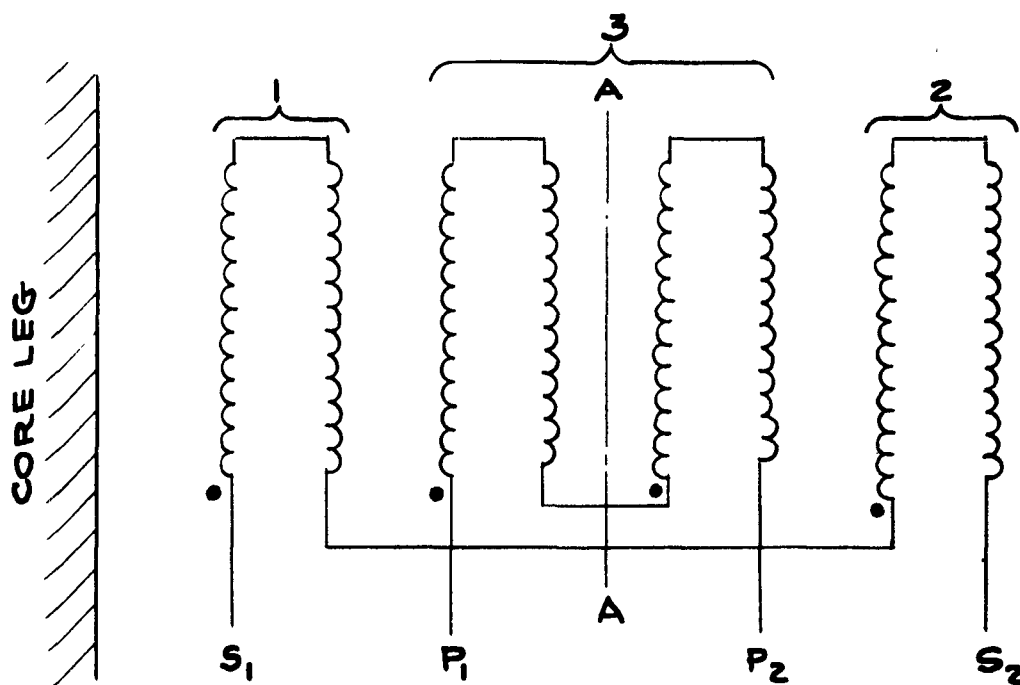2. Wind coils so dotted terminals have the same instantaneous polarity.

EQUATIONS:

$$L_L = \frac{3.19 \, N_s^2 \, K_r \, A \, 10^{-8}}{h} \text{ HENRIES}$$

$$A = \ell_{12} \, S_{12} + \frac{\ell_1 \, D_1}{3} + \frac{\ell_2 \, D_2}{3}$$

$$C_d = \frac{0.075 \, h}{E_s^2} \left[\frac{4 \ell_1 \, K_1 \, (m_1 - 1) \, V_1^2}{S_1 \, m_1^2} + \frac{4 \ell_2 \, K_2 \, (m_2 - 1) \, V_2^2}{S_2 \, m_2^2} \right.$$

$$\left. + \frac{\ell_{12} \, K_{12}}{S_{12}} \left[(V_{12}')^2 + (V_{12}')(V_{12}'') + (V_{12}'')^2 \right] \right] \text{ PF}$$

FIG. 1

CORE LEG

1 3 A 2

S₁ P₁ P₂ S₂

(labels: S₁ P₁ P₂ S₂; axis A–A)

NOTES:

1. The winding traverse for all layers is the same.

2. Wind coils so dotted terminals have the same instantaneous polarity.

3. Windings are symmetrical around A-A.

EQUATIONS:

$$L_L = \frac{3.19\, N_s^2\, K_r\, A\, 10^{-8}}{h} \quad \text{HENRIES}$$
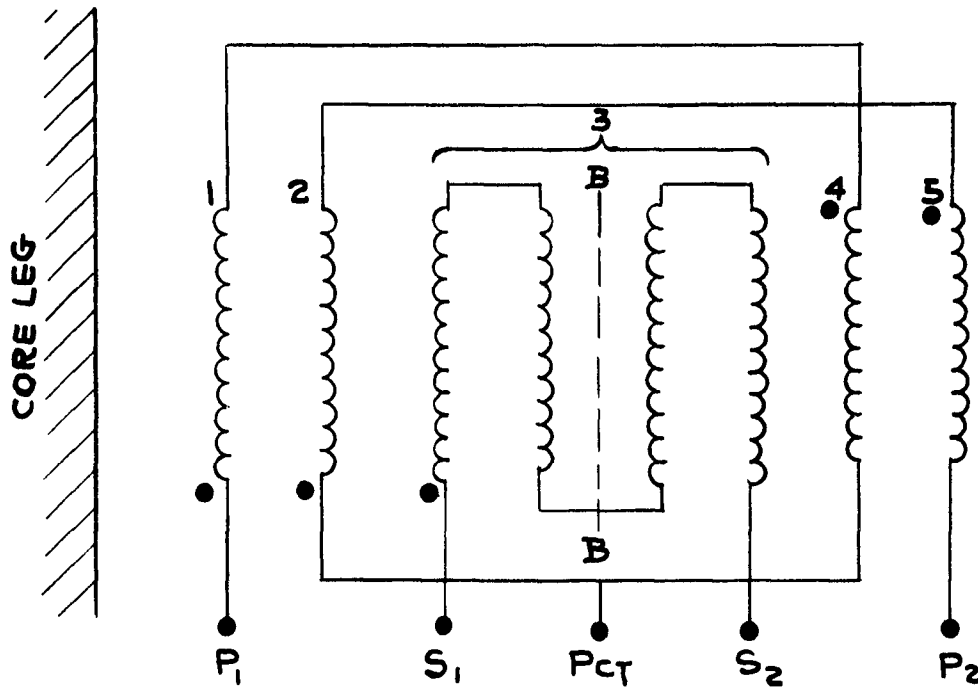
$$A = \frac{\ell_3}{2}\left(S_{13} + \frac{D_1}{3} + \frac{D_3}{6}\right)$$

$$C_d = \frac{0.075\, h}{E_s^2}\left[\frac{8\,\ell_3\, K_1\,(m_1-1)\, V_1^2}{S_1 m_1^2} + \frac{4\,\ell_3\, K_3\,(m_3-1)\, V_3^2}{S_3 m_3^2}\right.$$
$$\left. + \frac{K_{13}}{S_{13}}\left(\ell_{13}\, B_1 + \ell_{23}\, B_2\right)\right] \quad \text{PF}$$

FIG. 2

$$B_1 = \left(V_{13}^{\prime}\right)^2 + \left(V_{13}^{\prime}\right)\left(V_{13}^{\prime\prime}\right) + \left(V_{13}^{\prime\prime}\right)^2$$

$$B_2 = \left(V_{23}^{\prime}\right)^2 + \left(V_{23}^{\prime}\right)\left(V_{23}^{\prime\prime}\right) + \left(V_{23}^{\prime\prime}\right)^2$$

FIG. 3

NOTES:

1. The winding traverse for all layers is the same.

2. Wind coils so dotted terminals have the same instantaneous polarity.

3. Windings are symmetrical around B-B.

EQUATIONS:

$$L_L = \frac{3.19 \, N_s^2 \, K_r \, A \, 10^{-8}}{h} \quad \text{HENRIES}$$

$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$A = \ell_3 \left(\frac{S_{12}}{2} + \frac{D_1}{3} \right)$$

$\frac{1}{2}$ PRIMARY TO SECONDARY

FOR $P_1 - P_{CT}$

$$A = \frac{1}{4} \left(\ell_{13} S_{13} + \ell_{34} S_{34} \right) + \frac{1}{12} \left(\ell_1 D_1 + \ell_3 D_3 + \ell_4 D_4 \right)$$

FOR $P_2 - P_{CT}$

$$A = \frac{1}{4}\left(\ell_{23} S_{23} + \ell_{35} S_{35}\right) + \frac{1}{12}\left(\ell_2 D_2 + \ell_3 D_3 + \ell_5 D_5\right)$$

DISTRIBUTED CAPACITANCE
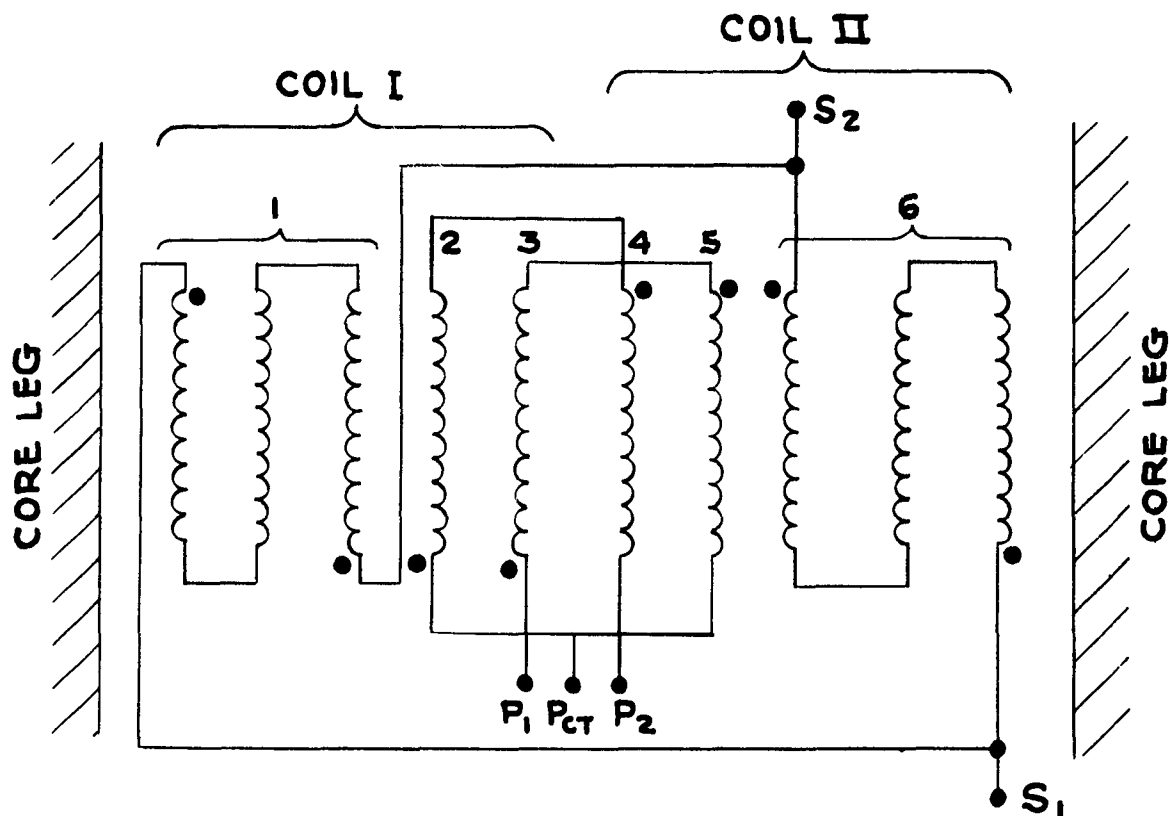
$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$C_{dp} = \frac{1.80\, h\, K_{12}\, V_1^2\, \ell_3}{E_S^2\, S_{12}} \quad PF$$

SECONDARY

$$C_{ds} = \frac{0.150\, h\, \ell_3}{E_S^2} \left[\frac{2\, K_3\,(m_3 - 1)\, V_3^2}{S_3\, m_3^2} \right.$$

$$\left. + \frac{K_{23}}{S_{23}}\left(B_1 + B_2\right) \right] PF$$

WHERE $B_1 = \left(V_{23}'\right)^2 + \left(V_{23}'\right)\left(V_{23}''\right) + \left(V_{23}''\right)^2$

WHERE $B_2 = \left(V_{34}'\right)^2 + \left(V_{34}'\right)\left(V_{34}''\right) + \left(V_{34}''\right)^2$

NOTES:

1. The traverse for all winding layers is the same.

2. Wind coils so dotted terminals have the same instantaneous polarity.

3. Coil I and Coil II are identical.

EQUATIONS:

LEAKAGE INDUCTANCE

$$L_L = \frac{3.19 \, N_s^2 \, K_r \, A \, 10^{-8}}{h} \quad \text{HENRIES}$$

$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$A = \ell_{23} \left(\frac{S_{23}}{2} + \frac{D_2}{3} \right)$$

FIG. 4

½ PRIMARY TO SECONDARY

$$A = \frac{\ell_{12} S_{12}}{4} + \frac{\ell_{13} S_{13}}{4} + \frac{\ell_1 D_1}{6} + \frac{\ell_{23} D_2}{6}$$

DISTRIBUTED CAPACITANCE

½ PRIMARY TO ½ PRIMARY

$$C_{dp} = \frac{1.80 \, h \, \ell_{23} \, K_{23} \, V_2^2}{S_{23} \, E_S^2} \quad PF$$

SECONDARY

$$C_{ds} = \frac{0.075 \, h}{E_S^2} \left[\frac{8 \ell_1 K_1 (m_1 - 1) V_1^2}{S_1 m_1^2} + \frac{\ell_{12} K_{12}}{S_{12}} [B_1 + B_2] \right] PF$$

$$B_1 = \left(V_{12}' \right)^2 + \left(V_{12}' \right)\left(V_{12}'' \right) + \left(V_{12}'' \right)^2$$

$$B_2 = \left(V_{56}' \right)^2 + \left(V_{56}' \right)\left(V_{56}'' \right) + \left(V_{56}'' \right)^2$$

$$V'_{12} = .33\ E_s - (-.25\ E_s) = .58\ E_s$$

$$V''_{12} = 0$$

$$V'_{23} = .25\ E_s - (-.25\ E_s) = .5\ E_s$$

$$V''_{23} = .5\ E_s$$

$$V'_{45} = .25\ E_s - (-.25\ E_s) = .5\ E_s$$

$$V''_{45} = .5\ E_s$$
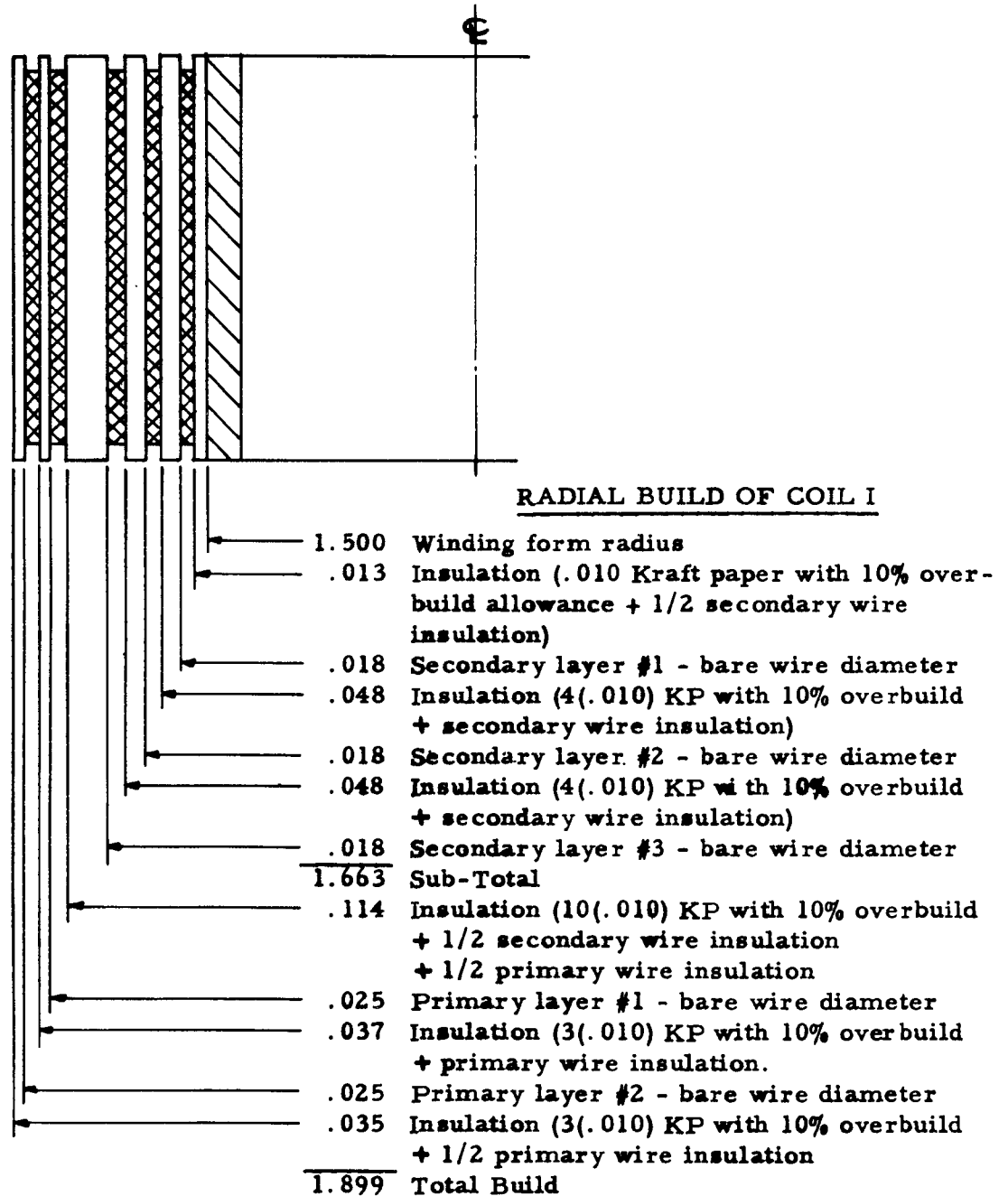
$$V'_{56} = .25\ E_s$$

$$V''_{56} = .33\ E_s$$

FIG. 4A

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RADIAL BUILD OF COIL I

1.500	Winding form radius
.013	Insulation (.010 Kraft paper with 10% over-build allowance + 1/2 secondary wire insulation)
.018	Secondary layer #1 - bare wire diameter
.048	Insulation (4(.010) KP with 10% overbuild + secondary wire insulation)
.018	Secondary layer #2 - bare wire diameter
.048	Insulation (4(.010) KP with 10% overbuild + secondary wire insulation)
.018	Secondary layer #3 - bare wire diameter
1.663	Sub-Total
.114	Insulation (10(.010) KP with 10% overbuild + 1/2 secondary wire insulation + 1/2 primary wire insulation
.025	Primary layer #1 - bare wire diameter
.037	Insulation (3(.010) KP with 10% overbuild + primary wire insulation.
.025	Primary layer #2 - bare wire diameter
.035	Insulation (3(.010) KP with 10% overbuild + 1/2 primary wire insulation
1.899	Total Build

FIG. 4B

CORE LEG

CORE LEG

S_2

| 1 | 2 | 3 | 4 | 5 | 6 |

P_1 P_{CT} P_2 S_1

PER UNIT MMF

1.0
0.75
0.50
0.25
0

$|D_2|S_{23}|D_3|$ $|D_4|S_{45}|D_5|$

MMF DIAGRAM ½ PRIMARY TO ½ PRIMARY

PER UNIT MMF

1.0
0.75
0.50
0.25
0

$|$ D_1 $|S_{12}|D_2|$ $|D_4|$ S_{46} $|$ D_6 $|$
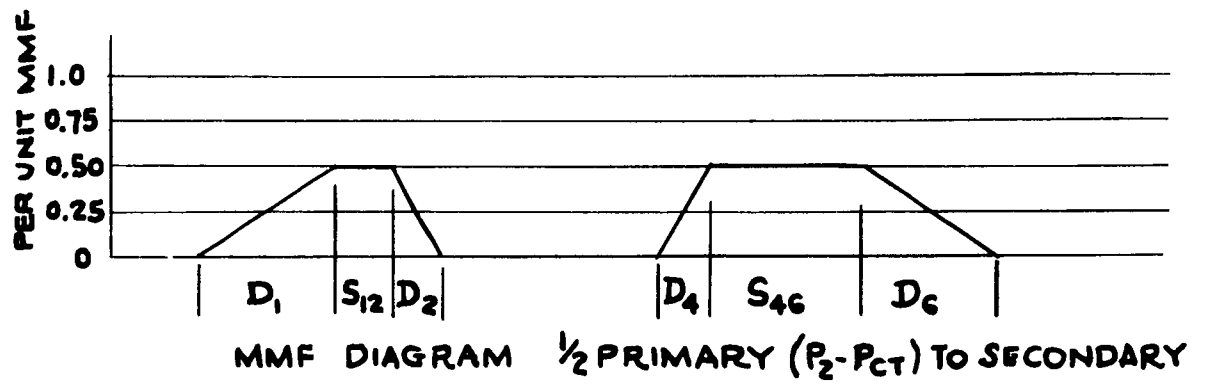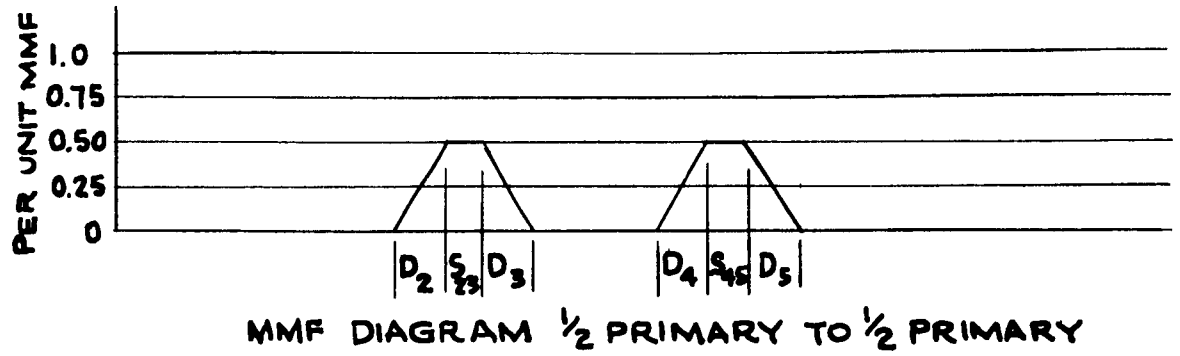
MMF DIAGRAM   ½ PRIMARY (P_2-P_{CT}) TO SECONDARY
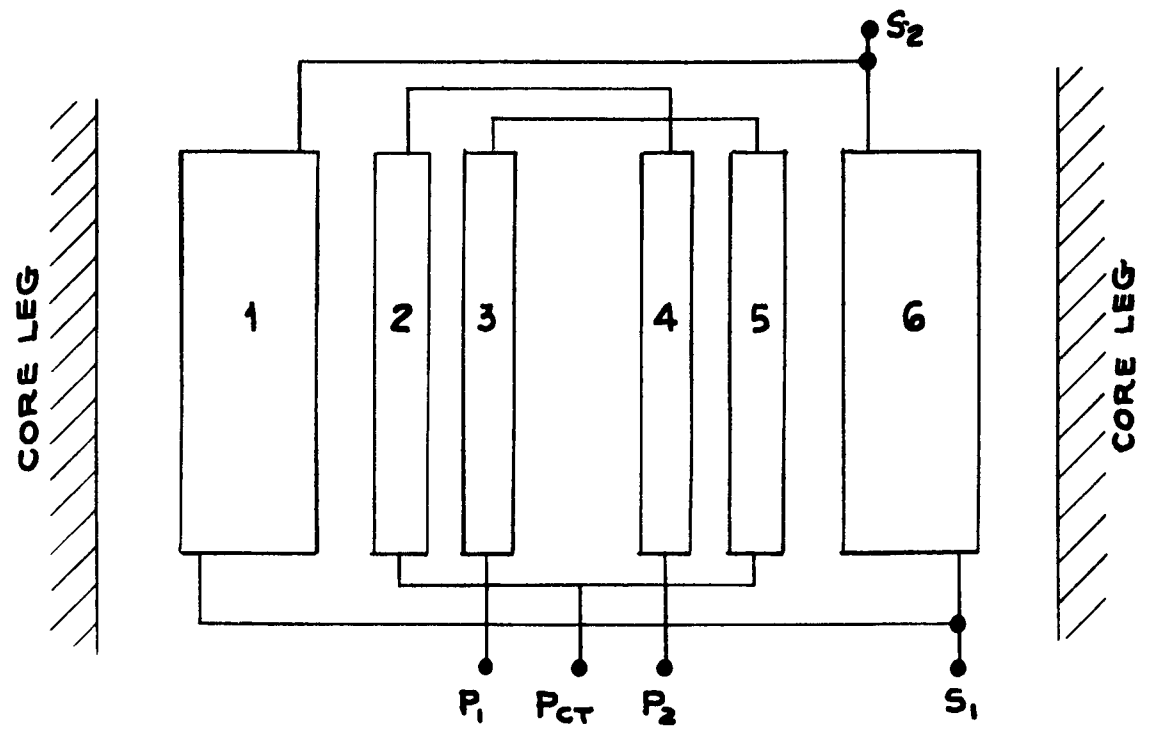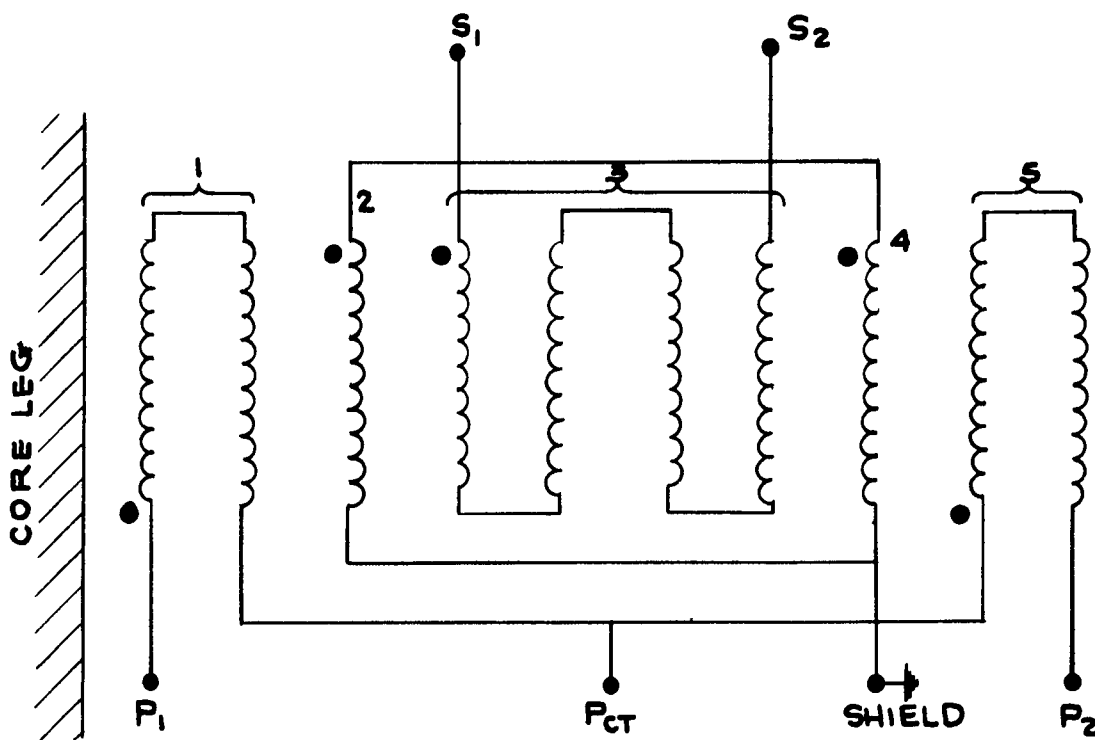
FIG. 4C

NOTES:

1. The winding traverse for all layers is the same.

2. Wind coil so dotted terminals have the same instantaneous polarity.

3. Patent #2,553,324

EQUATIONS:

$$L_L = \frac{3.19\, N_s^2\, A\, 10^{-8}}{h} \quad \text{HENRIES}$$

$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$A = \ell_3 \left\{ K_{r15}\left(S_{15} + \frac{2D_1}{3}\right) - \frac{\left[K_{r12}\left(\frac{D_1}{3} + S_{12} + \frac{D_2}{3}\right) - K_{r14}\left(\frac{D_1}{3} + S_{14} + \frac{D_2}{3}\right)\right]^2}{K_{r24}\left(S_{24} + \frac{2D_2}{3}\right)} \right\}$$

WHEN K_{r15}, K_{r12}, K_{r14} AND $K_{r24} \approx 1$

$$A = \ell_3 \left[S_{15} + \frac{2D_1}{3} - \frac{(S_{12} - S_{14})^2}{S_{24} + \frac{2D_2}{3}} \right]$$

FIG. 5

½ PRIMARY TO SECONDARY

FOR $P_1 - P_{CT}$

$$A = K_{r13}\left(\frac{\ell_1 D_1}{3} + \frac{\ell_3 D_3}{3} + \ell_{13} S_{13}\right) - \left\{K_{r12}\left[\frac{\ell_1 D_1}{3} + \frac{\ell_2 D_2}{3} + \ell_{12} S_{12}\right] - K_{r14}\left[\frac{\ell_1 D_1}{3} + \frac{\ell_4 D_4}{3} + \ell_{14} S_{14}\right] - K_{r23}\left[\frac{D_2}{3}(\ell_2 - \ell_4) + S_{23}(\ell_{23} - \ell_{34})\right]\right\}^2$$

$$4 K_{r24}\, \ell_3\left(S_{24} + \frac{2D_2}{3}\right)$$

WHEN $K_{r13}, K_{r12}, K_{r14}, K_{r23}$ AND $K_{r24} \approx 1$

$$A = \frac{\ell_1 D_1}{3} + \frac{\ell_3 D_3}{3} + \ell_{13} S_{13} - \frac{[\ell_{12} S_{12} - \ell_{14} S_{14} - S_{23}(\ell_{23} - \ell_{34})]^2}{4\ell_3\left(S_{24} + \frac{2D_2}{3}\right)}$$

FOR $P_2 - P_{CT}$

$$A = K_{r35}\left(\frac{\ell_3 D_3}{3} + \frac{\ell_5 D_5}{3} + \ell_{35} S_{35}\right) - \left\{K_{r45}\left[\frac{\ell_4 D_4}{3} + \frac{\ell_5 D_5}{3} + \ell_{45} S_{45}\right] - K_{r25}\left[\frac{\ell_2 D_2}{3} + \frac{\ell_5 D_5}{3} + \ell_{25} S_{25}\right] - K_{r23}\left[\frac{D_2}{3}(\ell_4 - \ell_2) + S_{23}(\ell_{34} - \ell_{23})\right]\right\}^2$$

$$4 K_{r24}\, \ell_3\left(S_{24} + \frac{2D_2}{3}\right)$$

WHEN $K_{r35}, K_{r45}, K_{r25}, K_{r23}$ AND $K_{r24} \approx 1$

$$A = \frac{\ell_3 D_3}{3} + \frac{\ell_5 D_5}{3} + \ell_{35} S_{35} - \frac{[\ell_{45} S_{45} - \ell_{25} S_{25} - S_{23}(\ell_{34} - \ell_{23})]^2}{4\ell_3\left(S_{24} + \frac{2D_2}{3}\right)}$$
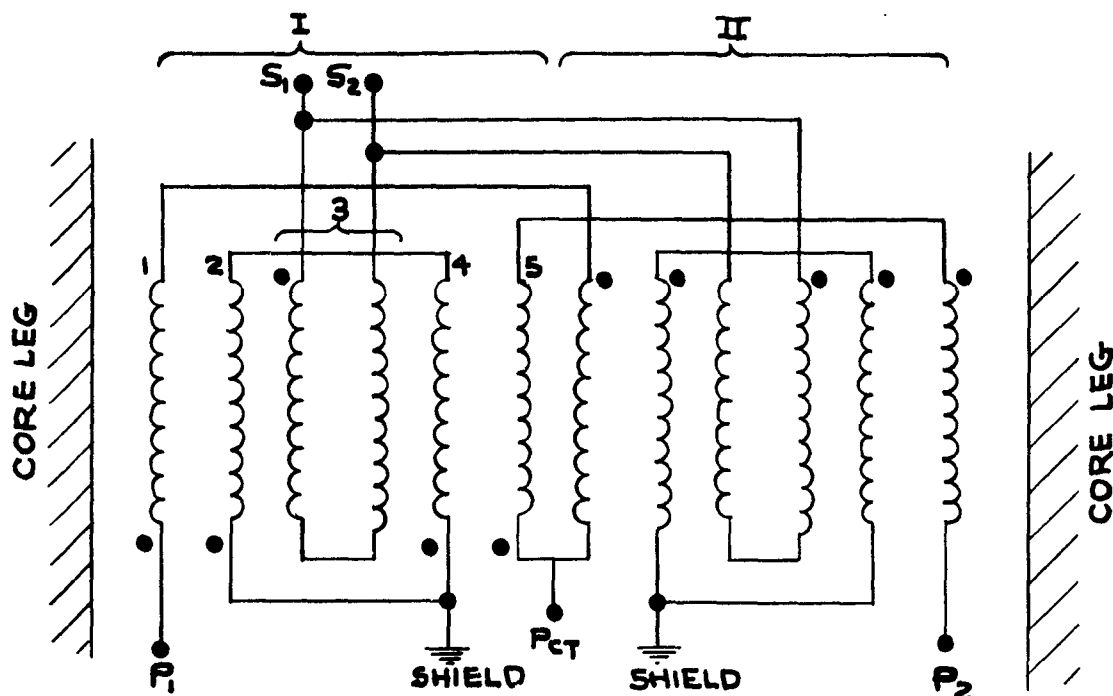
DISTRIBUTED CAPACITANCE

½ PRIMARY TO ½ PRIMARY = 0

SECONDARY

$$C_{ds} = \frac{0.075\, h}{E_s^2}\left[\frac{4\ell_3 K_3(m_3 - 1)\, V_3^2}{S_3 m_3^2} + \frac{K_{23}}{S_{23}}\left(\ell_{23}\, B_1 + \ell_{34}\, B_2\right)\right]$$

$$B_1 = (V_{23}')^2 + (V_{23}')(V_{23}'') + (V_{23}'')^2$$

I   II

S_1 S_2

CORE LEG

3

1   2   4   5

CORE LEG

P_1 SHIELD P_{CT} SHIELD P_2

NOTES:

1. The winding traverse for all layers is the same.

2. Wind coils so dotted terminals have the same instantaneous polarity.

3. Coil I and Coil II are identical.

4. Patent #2,553,324

5. Assume $S_{12} = S_{45}$, $S_{23} = S_{34}$, $D_1 = D_5$, $D_2 = D_4$

EQUATIONS:

$$L_L = \frac{3.19 \ N_s^2 \ A \ 10^{-8}}{h} \quad \text{Henries}$$

1/2 Primary to 1/2 primary

$$A = \ell_3 \left\{ K_{r15}\left(\frac{S_{15}}{2} + \frac{D_1}{3}\right) - \frac{\left[K_{r12}\left(\frac{D_1}{3} + S_{12} + \frac{D_3}{3}\right) - K_{r14}\left(\frac{D_1}{3} + S_{14} + \frac{D_2}{3}\right)\right]^2}{2 K_{r24}\left(S_{24} + \frac{2D_2}{3}\right)} \right\}$$

when K_{r15}, K_{r12}, K_{r14} and $K_{r24} \approx 1$

$$A = \ell_3 \left[\frac{S_{15}}{2} + \frac{D_1}{3} - \frac{(S_{12} - S_{14})^2}{2\left(S_{24} + \frac{2D_2}{3}\right)}\right]$$

FIG. 6

1/2 Primary to Secondary

$$A = \ell_3 \left[\left(S_{13} + \frac{D_1}{3} + \frac{D_3}{6} \right) - \frac{(S_{14} - S_{12})^2}{8 \left(\frac{S_{24}}{2} + \frac{D_2}{3} \right)} \right]$$
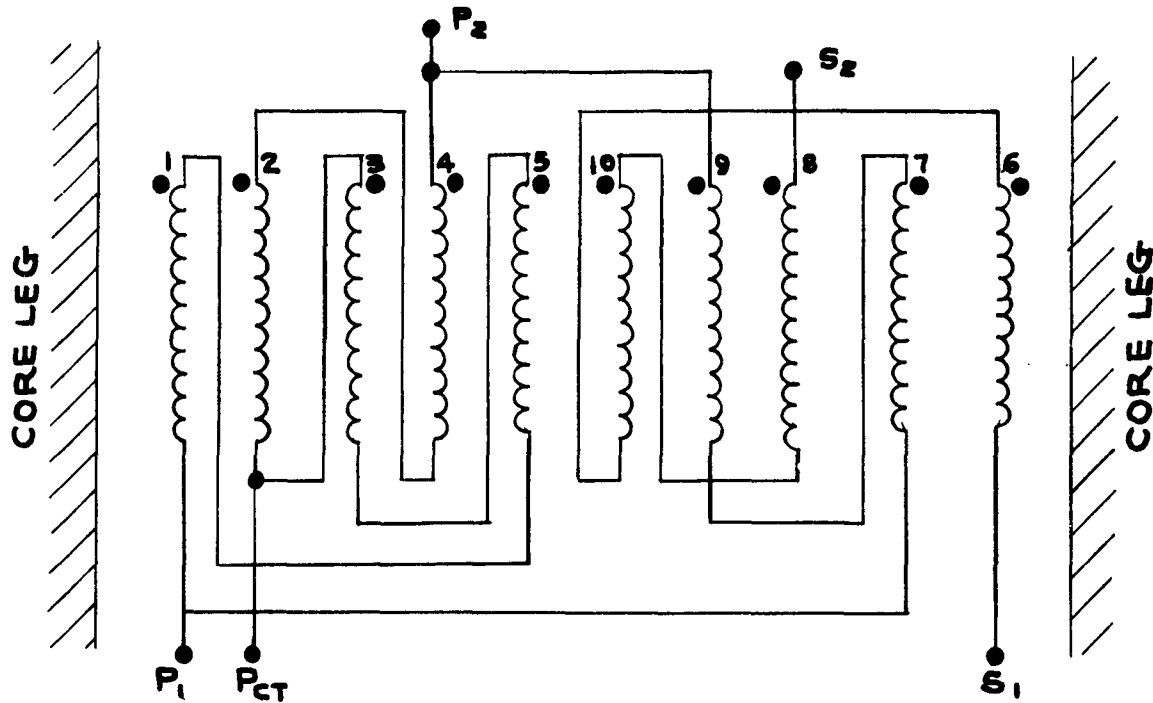
Distributed Capacitance

1/2 Primary to 1/2 Primary $= 0$

Secondary

$$C_{ds} = \frac{0.150h}{E_s^2} \left[\frac{4 \ell_3 K_3 (m_3 - 1) V_3^2}{S_3 m_3^2} + \frac{K_{23}}{S_{23}} \left(\ell_{23} B_1 + \ell_{34} B_2 \right) \right] \text{ PF}$$

where $B_1 = (V_{23}')^2 + (V_{23}')(V_{23}'') + (V_{23}'')^2$

$$B_2 = (V_{34}')^2 + (V_{34}')(V_{34}'') + (V_{34}'')^2$$

FIG. 7

NOTES:

1. The winding traverse for all layers is the same.

2. Wind coils so dotted terminals have the same instantaneous polarity.

3. All insulation pads (S) are equal.

EQUATIONS:

$$L_L = \frac{3.19\ N_s^2\ K_r\ A\ 10^{-8}}{h}\ \text{HENRIES}$$

$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$A = \frac{\ell_3}{6}\left(\frac{D_1}{2} + \frac{D_2}{3} + \frac{5S_{12}}{3}\right)$$

$\frac{1}{2}$ PRIMARY TO SECONDARY

$$A = \frac{C\ell_3}{6}\left(\frac{D_1}{2} + \frac{D_2}{3} + \frac{SS_{12}}{3}\right) + \frac{\ell_8}{6}\left(\frac{D_6}{2} + \frac{D_7}{3} + \frac{SS_{67}}{3}\right)$$

WHERE $C = \left(\frac{\frac{1}{2}\ \text{PRIMARY TURNS}}{\text{SECONDARY TURNS}}\right)^2$

DISTRIBUTED CAPACITANCE

$\frac{1}{2}$ PRIMARY TO $\frac{1}{2}$ PRIMARY

$$C_d = \frac{0.075\, h\, K_{12}}{S_{12}\, E_S^2}\left[\ell_{12} B_1 + \ell_{23} B_2 + \ell_{34} B_3 + \ell_{45} B_4\right]\ \text{PF}$$

WHERE $B_1 = \left(V_{12}'\right)^2 + \left(V_{12}'\right)\left(V_{12}''\right) + \left(V_{12}''\right)^2$

$\qquad B_2 = \left(V_{23}'\right)^2 + \left(V_{23}'\right)\left(V_{23}''\right) + \left(V_{23}''\right)^2$

$\qquad B_3 = \left(V_{34}'\right)^2 + \left(V_{34}'\right)\left(V_{34}''\right) + \left(V_{34}''\right)^2$

$\qquad B_4 = \left(V_{45}'\right)^2 + \left(V_{45}'\right)\left(V_{45}''\right) + \left(V_{45}''\right)^2$

SECONDARY

$$C_d\ \text{SEC} = \frac{0.075\, h}{E_S^2}\left[\frac{12\, K_6\, \ell_8\, (m_6 - 1)\, V_6^2}{S_6\, m_6^2} + \frac{K_{67}}{S_{67}}\left(\ell_{67} B_5 + \ell_{78} B_6 + \ell_{89} B_7 + \ell_{9\text{-}10} B_8\right)\right]\ \text{PF}$$

WHERE $B_5 = \left(V_{67}'\right)^2 + \left(V_{67}'\right)\left(V_{67}''\right) + \left(V_{67}''\right)^2$

$\qquad B_6 = \left(V_{78}'\right)^2 + \left(V_{78}'\right)\left(V_{78}''\right) + \left(V_{78}''\right)^2$

$\qquad B_7 = \left(V_{89}'\right)^2 + \left(V_{89}'\right)\left(V_{89}''\right) + \left(V_{89}''\right)^2$

$\qquad B_8 = \left(V_{9\text{-}10}'\right)^2 + \left(V_{9\text{-}10}'\right)\left(V_{9\text{-}10}''\right) + \left(V_{9\text{-}10}''\right)^2$

COMPARISON OF CALCULATED AND MEASURED VALUES OF LEAKAGE INDUCTANCE

	Measured L_L Millihenries	Calculated L_L Millihenries
Coil #1 (Ref. Figure 1)	4.2	4.15
Coil #2 (Ref. Figure 2)	1.53	1.54
Coil #3 (Ref. Figure 3)		
1/2 Primary to 1/2 Primary	.52	.48
1/2 Primary to Sec. (P_1-P_{CT} to S_1-S_2)	1.54	1.58
1/2 Primary to Sec. (P_2-P_{CT} to S_1-S_2)	1.72	1.67
Coil #4 (Ref. Figure 4)		
1/2 Primary to 1/2 Primary	.49	.506
1/2 Primary to Sec. (P_1-P_{CT} to S_1-S_2)	1.76	1.74
1/2 Primary to Sec. (P_2-P_{CT} to S_1-S_2)	1.76	1.74
Coil #5 (Ref. Figure 5)		
1/2 Primary to 1/2 Primary	9.2	5.65
1/2 Primary to Sec. (P_1-P_{CT} to S_1-S_2)	4.88	3.98
1/2 Primary to Sec. (P_2-P_{CT} to S_1-S_2)	6.00	4.88
Coil #6 (Ref. Figure 5)		
1/2 Primary to 1/2 Primary	7.68	7.45
1/2 Primary to Sec. (P_1-P_{CT} to S_1-S_2)	5.16	5.43
1/2 Primary to Sec. (P_2-P_{CT} to S_1-S_2)	7.12	6.90
Coil #7 (Ref. Figure 7)		
1/2 Primary to 1/2 Primary	.28	.275
1/2 Primary to Secondary	1.42	1.44
1/2 Primary to Secondary	1.42	1.44

FIG. 8

REFERENCES

1. Blume, Boyajian, Camilli. Lennox, Minneci, and Montsinger, "Transformer Engineering", John Wiley & Sons, Inc., New York, N.Y. (1951).

2. Rogowski, W., "Mitteilungen veber Forschungsarbeiten", 1909, Heft 71.

3. Fessler, Lasher, Lord, and Walters, "Transformer Design Criteria and Data" (Part of Final Report, Transformer Development, High Frequency), Report No. RL.417, June 1950, U.S. Army Signal Corps, Contract No. W-36-039-sc-38268.

4. United States Patent No. 2,553,324; H. W. Lord, May 15, 1951.

5. United States Patent No. Re.24,474; W. W. Wahlgren, May 20, 1958.

EXHIBIT 3

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

SAMPLE LEAKAGE INDUCTANCE CALCULATION USING THE METHOD OF H. O. STEPHENS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NOBsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ⬤ ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASSACHUSETTS

SAMPLE LEAKAGE INDUCTANCE CALCULATION USING THE METHOD OF H. O. STEPHENS

A method devised by H. O. Stephens, for the calculation of leakage inductance, was outlined in Exhibit I of the First Quarterly Report. This method, used to calculate the leakage inductance of transformers having winding layers of different lengths and/or tapped out sections, is further clarified by the following sample calculation.

The leakage inductance calculation requires the use of equations (4), (6), and (8) of Exhibit I. These are repeated here for convenience.

The leakage area associated with the space (S) between windings is

$$A_s \;=\; \left(\frac{N_1 I_1}{N_s I_s}\right)^2 \quad A_1 \;=\; \left(\frac{N_1 I_1}{N_s I_s}\right)^2 \; \ell_1 S_1 \tag{4}$$

Where $\left(\dfrac{N_1 I_1}{N_s I_s}\right)$ is the per unit mmf acting on the space (S_1) between

the two windings and ℓ_1 is the mean length of the space.

The leakage area associated with each winding build is

$$A_w \;=\; \ell_c d \left[\frac{(N_1 I_1)^2 + (N_1 I_1)(N_2 I_2) + (N_2 I_2)^2}{3 (N_s I_s)^2}\right] \tag{6}$$

which can be rewritten

$$A_w \;=\; \frac{\ell_c d}{3} \left[\left(\frac{N_1 I_1}{N_s I_s}\right)^2 + \left(\frac{N_1 I_1}{N_s I_s}\right)\left(\frac{N_2 I_2}{N_s I_s}\right) + \left(\frac{N_2 I_2}{N_s I_s}\right)^2\right] \tag{6A}$$

Here ℓ_c is the mean length of turn of the winding in question, d is the total radial build of the winding, $\left(\dfrac{N_1 I_1}{N_s I_s}\right)$ is the per unit mmf one side of

the winding, and $\left(\dfrac{N_2 I_2}{N_s I_s}\right)$ is the per unit mmf on the other side of the winding.

$$L_L \;=\; \frac{3.19 \; N_s^2 \; K_r \; (A_s + A_w) \; 10^{-8}}{h} \quad \text{Henries} \tag{8}$$

Where L_L is the leakage inductance referred to the winding having N_g turns, K_r is the Rogowski correction factor, and A_g and A_w are the leakage areas defined by equations (4) and (6A) above.

For this example, assume that the leakage inductance of the transformer described in figure 1 is desired. Because the secondary winding is shorter than the primary winding, and has a missing or tapped out section, the equations listed above do not apply, and Stephens method must be used. The outline shown on page 6, Exhibit I, of the First Quarterly Report will be followed. All values will be referred to the secondary winding.

<u>STEP 1</u>

Assume the transformer is as shown in figure 2. Note that the traverse of the secondary is the same as the primary, and there is no tapped out section. The leakage inductance of the transformer can be calculated using equations (4), (6A), and (8).

Substituting in equation (4), the leakage area between windings is

$$A_g = (1.0)^2 (12.7) (0.250) = 3.18 \text{ sq. in.}$$

Substituting in equation (6A) the leakage area in the primary winding is

$$A_{wp} = \frac{(12) (0.400)}{3} \left[(1.0)^2 + (1.0) (0) + (0)^2 \right]$$
$$= 1.60 \text{ sq. inches}$$

and in the secondary winding

$$A_{ws} = \frac{(13.2) (0.200)}{3} \left[(0)^2 + (0) (1.0) + (1.0)^2 \right]$$
$$= 0.88 \text{ sq. inches}$$

The total leakage area is the sum of the areas obtained above or

$$A_g + A_w = 3.18 + 1.60 + 0.88 = 5.66 \text{ sq. inches}$$

The Rogowski correction factor can be obtained from figure 7, Exhibit 1, of the First Quarterly Report where

$$\frac{h}{b} = \frac{6.00}{0.850} = 7.06$$

From figure 7

$$K_r = 0.95$$

Substituting in equation (8), the leakage inductance is:

$$L_{L1} = \frac{(3.19)(100)^2 (0.95)(5.66) 10^{-8}}{6.0} = 0.286 \text{ mhy}$$

To determine the effects of the shortened winding layer and tapped out section, follow steps 2 through 5.

STEP 2

Draw the secondary coil (S_1) as shown in figure 3A. This coil has the traverse or layer length of the coil assumed in step 1, but is assigned the per unit mmf distribution of the actual coil. Thus the extensions and tapped out center section have zero mmf.

STEP 3

Draw a second coil (S_2) having the same sections and dimensions as the one for step 2, but dividing the mmf linearly along the winding traverse. This is shown in figure 3B.

STEP 4

Draw a third coil (S_3) again having the same sections and dimensions as the one for step 2. The mmf of each section is the mmf of the same section of coil (S_1) minus coil (S_2). This is shown in figure 3C.

STEP 5

Referring to figure 3, assume that the negative mmf sections are one winding, and the positive mmf sections are another. This makes coil (S_3) a transformer having windings that are side by side (sometimes called disc coils) instead of one over another (concentric coils). By using the coil radial build as the winding traverse, all of the coils will have the same traverse, and equations (4), (6A), and (8) can be used to calculate the leakage inductance of this transformer.

Since there is no space between windings

$$A_s = 0$$

To calculate A_w from equation 6A, note that:

1. The mean length of turn (ℓ_c) is the same as the original secondary coil.

2. The traverse (h) is the build of the original coil, and the build (d) is the traverse of each section. Thus, for this example, (h) is 0.200 for each section and (d) is 1.0 for section 1, 3.0 for section 2, etc.

- 3 -

3. The per unit mmf $\frac{(N_1I_1)}{(N_sI_s)}$ is obtained by starting at one end and al-

gebraically adding the per unit mmf of each section, up to the section in question. The value of $\frac{(N_2I_2)}{(N_sI_s)}$ is $\frac{(N_1I_1)}{(N_sI_s)}$ plus the mmf of the section in question. Thus, for section 3

$$\frac{(N_1I_1)}{(N_sI_s)} = (-0.167) + (0.1) = -0.067$$

$$\frac{(N_2I_2)}{(N_sI_s)} = (-0.067) + (-0.083) = -0.150$$

With the above in mind, substitute in equation 6A to find A_w for each section.

$$A_{w1} = \frac{(13.2)\ (1.0)}{3}\left[(0)^2 + (0)(-0.167) + (-0.167)^2\right] = .123$$

$$A_{w2} = \frac{(13.2)\ (3.0)}{3}\left[(-0.167)^2 + (-0.167)(-0.067)+(-0.067)^2\right]=.576$$

$$A_{w3} = \frac{(13.2)(0.5)}{3}\left[(-0.067)^2 + (-0.067)(-0.150) + (-0.150)^2\right] =0.081$$

$$A_{w4} = \frac{(13.2)(1.0)}{3}\left[(-0.150)^2 + (-0.150)(0.083)+(0.083)^2\right] = 0.184$$

$$A_{w5} = \frac{(13.2)(0.5)}{3}\left[(0.083)^2 + (0.083)(0) + (0)^2\right] = 0.015$$

$$A_w = A_{w1} + A_{w2} + \ldots + A_{w5} = 0.979$$

The Rogowski correction factor is a function of the h/b ratio, where b is 1/2 the wave length of the mmf diagram. Therefore

$$\frac{h}{b} = \frac{0.200}{3.00} = 0.0667$$

Since this is outside the limits of the curve, the Rogowski correction factor is computed from the equation

$$K_r = 1 - \frac{1 - \mathcal{E}^{-\pi \frac{h}{b}}}{\frac{\pi h}{b}}$$

$$\coloneqq 1 - \frac{1 - \varepsilon^{-0.0667\,\pi}}{0.0667\,\pi} = 0.1$$

Substituting in equation (8), the leakage inductance is

$$L_{L2} = \frac{(3.19)\,(100)^2\,(0.1)\,(0.979)\,10^{-8}}{0.200} \quad \text{Henries}$$

$$\coloneqq 0.156 \text{ mhy}$$

This is the leakage inductance caused by the unequal winding layers and the tapped out section.

STEP 6

The leakage inductance of the transformer shown in figure 1 is the sum of the inductances calculated in steps 1 and 5. Therefore, the leakage inductance, referred to the secondary winding is

$$L_L = 0.286 + 0.156 \coloneqq 0.442 \text{ mhy}$$

This example also points out the importance of having winding layers of uniform length and no missing sections, if low leakage inductance is desired.
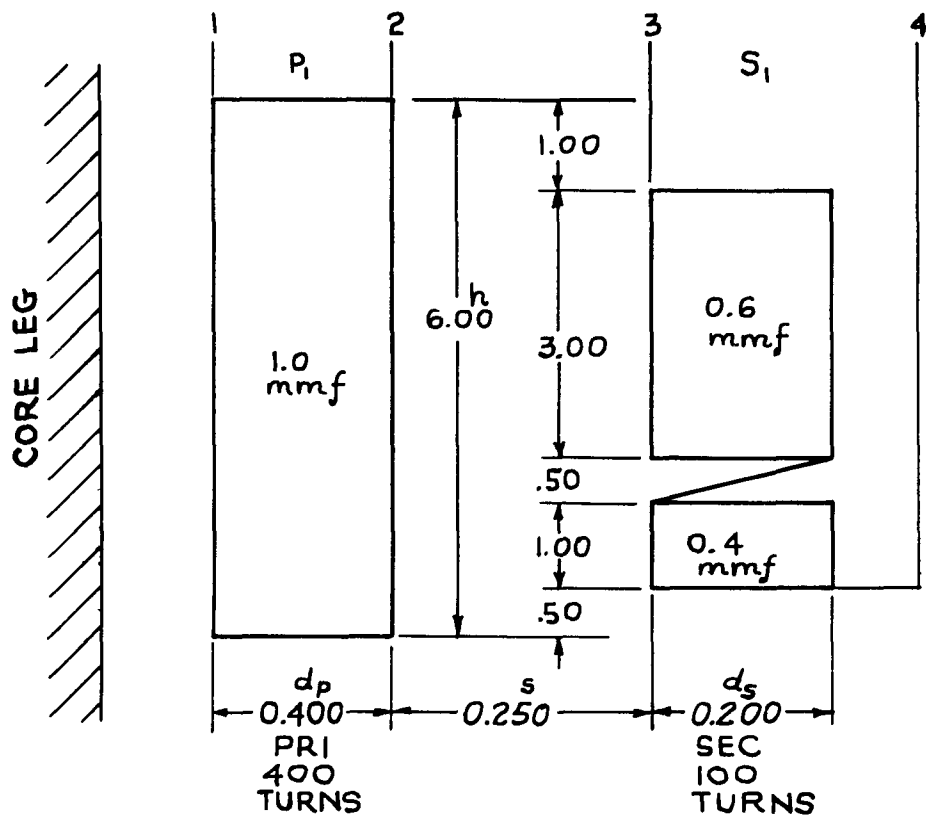
MEAN LENGTH OF PRIMARY TURN $\quad \ell_{cp} = 12$
MEAN LENGTH OF SECONDARY TURN $\quad \ell_{cs} = 13.2$
MEAN LENGTH OF INSULATION BETWEEN
WINDINGS $\quad \ell_s = 12.7$

FIGURE 1

FIGURE 2

CORE LEG

1   2   3   4

P_1 S_2

1.0 mmf h 6.0   1.0 mmf

d_p 0.400 — 400 TURNS s .250 d_s 0.200 — 100 TURNS
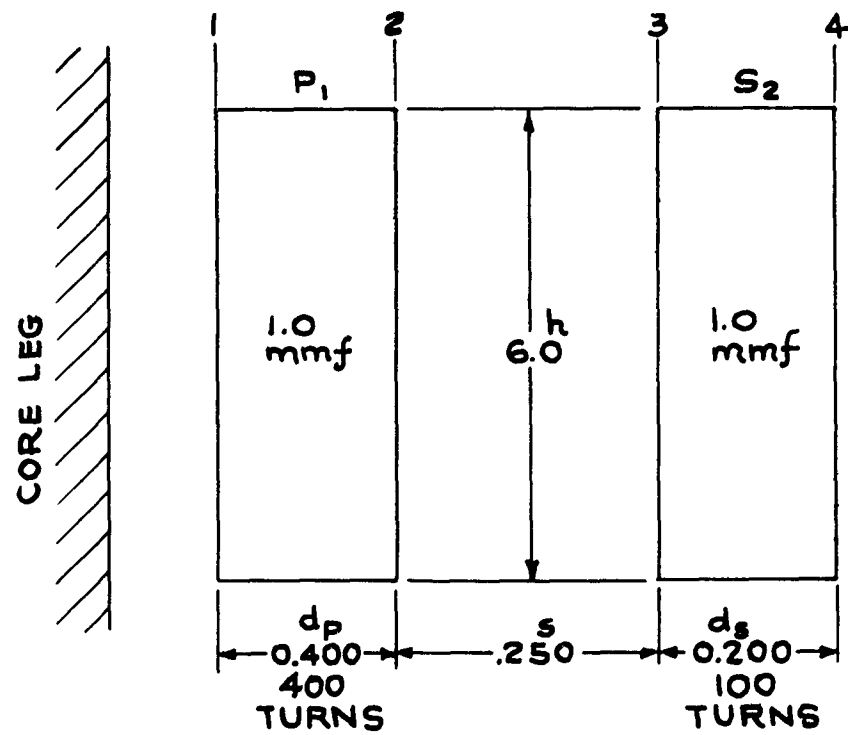
S_1		S_2	S_3	SECTION
0	1.0	$\frac{1}{6}$ = 0.167	-0.167	1
0.6	3.0	$\frac{3}{6}$ = 0.5	0.1	2
0	0.5	$\frac{0.5}{6}$ = .083	-0.083	3
0.4	1.0	$\frac{1}{6}$ = .167	0.233	4
0	0.5	$\frac{0.5}{6}$ = .083	-0.083	5

d_s .200 d_s .200 d_s .200

A   B   C

FIGURE 3